ECONOMIC GEOLOGY

VOL. XXXI JANUARY–FEBRUARY, 1936 No. 1

THE CINNABAR DEPOSITS IN SOUTHWESTERN ARKANSAS.[1]

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Most of the known cinnabar deposits of southwestern Arkansas lie near a regional thrust-fault, within a zone nearly 30 miles long and less than 2 miles wide, which extends completely across Pike County and into Clark County (Fig. 1).

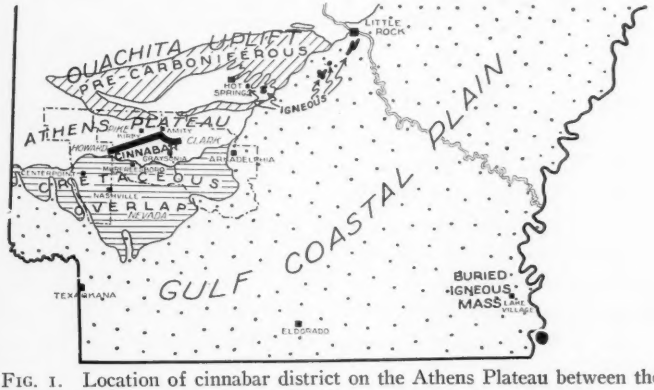


FIG. 1. Location of cinnabar district on the Athens Plateau between the Ouachita Mountains and the Cretaceous Overlap, Arkansas.

Details relating to the discovery and development of the district have already appeared in various publications,[2] the most

[1] Presented before the Society of Economic Geologists, New York joint meeting, February, 1935; manuscript received March 13, 1935.

[2] Weigel, W. M.: New Quicksilver Discoveries. Eng. & Min. Jour. vol. 132, pp. 495–497, 1931; Stearn, N. H.: The New Quicksilver District in Arkansas. Min.

recent of which is a preliminary report [3] by representatives of the United States Geological Survey.

FIELD WORK.

In August, 1931, Mr. Leo Yount secured an option on the hill in Section 1, T. 7 S., R. 26 W., where the original cinnabar specimen was found. He began to explore in the district by trenching and test-pitting, but soon encountered such perplexing structural complexities that in September, 1931, he retained the writer to report on the area and to act in an advisory capacity in the development of his properties.

Field work was begun October 3, 1931, with the assistance of Mr. L. L. Palmer. The necessity of making a detailed regional topographic and geologic map soon became apparent. In order to secure all the information which the surface could yield, the pacing traverse method of mapping was used. Traverses were run at 125-pace intervals, making 4 traverses to each 40 acres. Transit survey lines checked the location of the traverses. Elevations were mapped with a Paulin altimeter checked by repeated reoccupation of previous observation points, by reference to a camp barometer, and by level lines. Every observable bed-rock exposure was mapped on the scale of 20 inches to the mile, to show character, attitude, and extent.

When it became necessary to broaden the scope of the survey in order to secure an adequate conception of regional structure, the services of Dr. J. M. Hansell were added and the detailed mapping was extended for 3½ miles east and 8½ miles west of the Little Missouri River, covering approximately 22 square miles.

State Highway 27 from Hot Springs to Murfreesboro bisects the Athens Plateau with fresh road cuts. The stratigraphy of the 13-mile section along the road from the Novaculite out-

Jour. (Ariz.), vol. 16, no. 2, pp. 3, 4, 1932; Branner, G. C.: Cinnabar in Southwestern Arkansas. Ark. Geol. Survey Inf. Circ. 2, 1932; Stearn, N. H: Mining and Furnacing Quicksilver Ore. Eng. & Min. Jour. vol. 134, pp. 122–124, 1933.

[3] Hansell, J. M. and Reed, J. C.: Quicksilver Deposits near Little Missouri River, Southwest Arkansas. Amer. Inst. Min. Eng. Tech. Pub. 612, 1935.

crop to the Cretaceous Overlap was mapped on a scale of 10 feet to the inch, and the tops and bottoms of beds carefully observed after determining 13 different criteria [4] for sequence of superposition which are applicable to the sediments of this district.

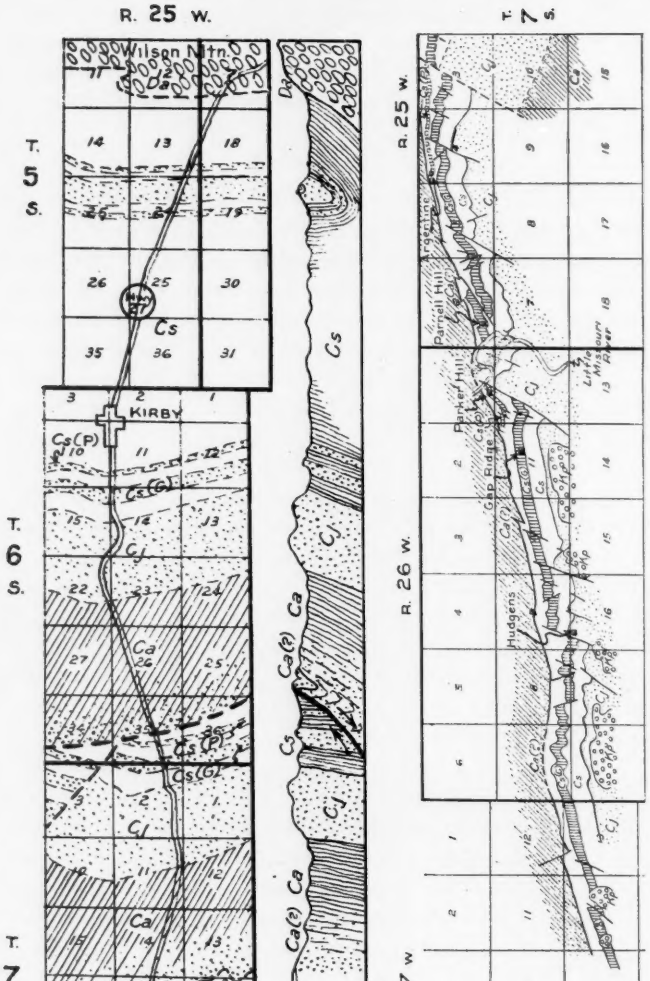
REGIONAL GEOLOGY.

The cinnabar deposits occur within the Athens Plateau,[5] which forms the south flank of the Ouachita Uplift, lying between the Ouachita Mountains and the Cretaceous Overlap of the Gulf Coastal Plain (Fig. 1). The westernmost end of the cinnabar district lies at the very edge of the Cretaceous Overlap; the eastern end lies more than 6 miles north of it. This fact has a definite topographic significance. The Cretaceous Overlap area is underlain by essentially flat-lying sediments, which in the Athens Plateau area are nearly vertical. The dendritic drainage patterns developed on the Cretaceous Overlap are modified to trellised drainage patterns where erosion has removed the Cretaceous sediments and exposed the pre-Cretaceous peneplain which truncates the edges of the up-ended earlier sediments. Subsequent erosion has etched the peneplain surface into about 300 feet of local relief controlled by the distribution of the resistant rocks, thus making topographic features structurally significant. But near the edge of the Cretaceous Overlap, the etching process has not had opportunity to proceed as far, and the topographic features in the extreme west end of the district have less structural significance. Fig. 7 illustrates the extent to which topography suggests structure near the Little Missouri River.

The rocks underlying the Athens Plateau compose an unusually thick series of alternating shale and sandstone beds, which overlie the Arkansas Novaculite of Devonian age. The series has been considered to be of Carboniferous age and lately it has been as-

[4] For a detailed description of one of these criteria see Stearn, N. H.: Structure from Sedimentation at Parnell Hill Quicksilver Mine, Arkansas. ECON. GEOL., vol. 29, pp. 146–156, 1934.

[5] Miser, H. D. and Purdue, A. H.: Geology of the DeQueen and Caddo Gap Quadrangles, Arkansas. U. S. Geol. Survey Bull. 808, 1929.



FIGS. 2 (above) AND 3 (below).

signed to the Pennsylvanian.[6] The shale-sandstone series represents the Arkansas equivalent of the Stanley, Jackfork, and Atoka formations which were named in Oklahoma,[7] but the general absence of distinctive marker horizons, especially in the eastern part of the Athens Plateau, the paucity of definitive fossils, and the complex structural conditions which have not yet been satisfactorily deciphered in detail, make it difficult to draw formation boundaries in terms of the Oklahoma terminology with any assurance.

Throughout the Athens Plateau the beds are generally steeply dipping,[8] standing nearly on end over most of the southern part of the area. The 15-mile width between the Arkansas Novaculite and the Cretaceous Overlap exposes the truncated edges of approximately 80,000 feet of clastic sediments. It is logical to infer that there has been repetition of beds; and this inference is confirmed by the presence near the Novaculite outcrop of open

[6] Harlton, B.: Carboniferous Stratigraphy of the Ouachitas, with Special Study of the Bendian. Bull. Amer. Assoc. Petr. Geol. vol. 18, pp. 1018–1037, 1934; Miser, H. D.: Carboniferous Rocks of Ouachita Mountains. *Idem*, pp. 971–993; White, D.: Age of Jackfork and Stanley Formations of Ouachita Geosyncline, Arkansas and Oklahoma, as Indicated by Plants. *Idem*, pp. 1010–1017.

[7] Taff, J. A.: U. S. Geol. Survey Atlas, Atoka Folio (No. 79), 1902.

[8] For an explanation of the occurrence of numerous low-angle dip observations, see Stearn, N. H.: Structure and Creep. Jour. Geol., vol. XLIII, no. 3, April–May, 1935.

FIG. 2. Section along State Highway 27 from the Ouachita Mountains to the Cretaceous Overlap. *Da*, Arkansas Novaculite (Devonian); *Cs*, Stanley Shale (Pennsylvanian); *Cs (G)*, Gap Ridge Sandstone, of Stanley Shale; *Cs (P)*, Parker Hill Sandstone, of Stanley Shale; *Cj*, Jackfork Sandstone (Pennsylvanian); *Ca*, Atoka Shale (Pennsylvanian); *Ca* (?), Atoka Sandstone or higher beds; *Kp*, Pike Gravel, Trinity Formation (Cretaceous).

FIG. 3. Geology of the west end of the cinnabar district. *Kp*, Pike Gravel, of Trinity Formation; *Ca* (?) Atoka Sandstone or higher beds; *Cj*, Jackfork Sandstone; *Cs*, Stanley Shale; *Cs (G)*, Gap Ridge member; *Cs (P)*, Parker Hill member. The Hudgens Mine is in Jackfork; the Gap Ridge and Parnell Hill Mines are in the Gap Ridge member of the Stanley; the Parker Hill and Argentine mines are in the Parker Hill member of the Stanley.

folding, the axis of which strikes EW. near the NE. corner of Section 24, T. 5 S., R. 25 W. (Fig. 2). But no evidence of close overturned folding with its concomitant fracture cleavage and intense dragfolding was observed along the section studied. From Kirby south to the Cretaceous Overlap, road-cut exposures and cinnabar-exploration trenches show the tops of the beds to be facing southward across the entire section except for a short distance in Section 35, T. 6 S., R. 25 W., where poorly exposed and ambiguous indications suggest that the tops of the beds may face northward.

Evidence assembled by the field work described above points to the conclusion that the repetition of the sedimentary series in the southern part of the Athens Plateau is effected by regional thrust-faulting from the south, the strike of which approximately parallels that of the bedding, and the concept derived from this field work and at present accepted [9] is that a major fault of this nature was the principal avenue of access to the mineralized solutions that deposited the cinnabar. This accounts for the linear distribution of the deposits.

The evidence supporting this structural concept is found in the stratigraphic sequence, the truncation of beds along their strike, and the juxtaposition of highly deformed beds against less deformed ones. These will be briefly summarized.

Stratigraphic Sequence.—Between Kirby and the Cretaceous Overlap, three prominent ridges strike slightly north of east. The first ridge, 1½ miles south of Kirby, is composed of rocks which differ from those north of it, being dominantly gray and quartzitic as compared with the soft white sandstones and shales near Kirby. The north edge of this ridge is assumed to mark the contact of the Stanley Shale with the Jackfork sandstone.

The stratigraphic sequence from the NE. corner of Section 15, T. 6 S., R. 25 W., to the center of Section 35, T. 6 S., R. 25 W., (Fig. 2) shows marked general similarity to that from the north line of Section 2, T. 7 S., R. 25 W., to the Cretaceous Overlap. The quartzitic Jackfork formation seems to underlie the first and

[9] Reference, footnote 3.

third of the ridges, and heretofore it has been assumed that the second ridge also contains Jackfork sandstone; but there now seems to be reason to believe that it may be underlain by Atoka or higher beds.

The middle ridge is neither as high nor as steep as the other two ridges. The tops of the beds seem to face southward, to a point about ¼ mile south of the north line of Section 35, T. 6 S., R. 25 W. Throughout the whole distance from Kirby to this point there seems to be a continuous sedimentary sequence. The shaly sequence (assumed to be Atoka) that appears just south of the northern Jackfork ridge becomes more sandy southward, seeming to grade into the massive sandstone formation which underlies the south half of the middle ridge. This massive sandstone resembles the Jackfork, but if assumed to be Jackfork it must have gotten there by thin slice faulting, which is unlikely, and of this little evidence is observable. On the other hand, it may logically be considered to be a sandy phase of the Upper Atoka, or a well developed phase of the Hartshorn, Ft. Smith, or even of the Savanna sandstone.[10] The "rice grain" conglomerates found in the middle ridge have counterparts not only in the Jackfork but also in the Winslow[11] (Upper Atoka) and the Savanna (above the Atoka), and therefore cannot be taken as determinative of Jackfork. Since the Atoka here is near the conjectured source of sedimentation,[12] and would be expected to be more coarsely clastic, it is logical to expect a high sandstone content.

Thus the stratigraphic sequence south of Kirby may be considered to be approximately as follows: Stanley Shale—7,500 ft. ±; Jackfork Sandstone—5,000 ft. ±; Atoka Shale and Sandstone, with possibly higher beds—7,500 + ft.; Stanley Shale—2,700 ft. ±; Jackfork Sandstone—5,000 ft. ±; Atoka Shale and Sandstone with possibly higher beds—9,000 + ft.[14]

[10] Croneis, C.: Geology of the Arkansas Paleozoic Area. Ark. Geol. Survey, Bull. 3.

[11] Miser, H. D. and Purdue, A. H.: *op. cit.*, p. 76.

[12] Llanoria or Llanoris. Dumble, E. T.: The Geology of East Texas. Tex. Univ. Bull. 1869, pp. 11–13, 1920; Miser, H. D.: Llanoria, The Paleozoic Land Area in Louisiana and Eastern Texas. Amer. Jour. Sci. (5), vol. 2, pp. 61–89, 1921.

[14] Croneis (see footnote 10) gives a possible thickness of 9,400 feet for the Atoka in Perry County, Arkansas.

Fig. 2 represents what seems to be the most reasonable interpretation of the known data, showing a regional thrust fault which brings upper Stanley into superposition upon what may be Upper Atoka or a higher formation. The possibility that this fault occurs near the axis of a syncline in the Atoka (?) is suggested on the basis of evidence for the syncline which cannot be considered conclusive.

Truncation.—The 2,700 ± ft. section of Upper Stanley is the principal formation underlying the cinnabar district itself. It contains two distinctive sandstone horizons, the Gap Ridge and Parker Hill members, named after the mines developed in them. From the top down, the log of this section of the Stanley shale may be summarized as follows:

Formation	*Thickness*	
Shaly zone	1,000 feet	
Sandy zone	100 feet	Gap Ridge sandstone member
Shaly zone	200 feet	
Sandy zone	300 feet	
Shaly zone	700 feet	
Sandy zone	175 feet	Parker Hill sandstone member
Shaly zone	200 feet ±	

Fig. 3 shows that the Gap Ridge member extends throughout the area mapped, whereas the Parker Hill member is cut out in Section 4, T. 7 S., R. 25 W., reappearing in Section 1, T. 7 S., R. 26 W., to be cut out again in Section 11, T. 7 S., R. 26 W. It may reappear again in the extreme west end of the district, where the erosional etching has not yet brought it into recognizable relief, but where cinnabar shines have been found in sandstone at about the equivalent horizon.

Relative Deformation.—It is notable that the Atoka (?) sandstone which forms the north boundary of the cinnabar district shows little deformation, whereas the Stanley shale (Fig. 3), and even the massive Jackfork sandstone south of it, show the effects of severe buckling and crumpling. This marked change in the degree of deformation is one of the criteria establishing the presence and location of the regional thrust fault.

A brief review of the inferred sequence of diastrophic events will aid in visualizing the structural features controlling the cinnabar deposition in the district.

TECTONIC HISTORY.

After the deposition of a thick series of clastic sediments in the Ouachita Geosyncline during middle Paleozoic and early Carboniferous time, mountain-building movements were initiated. They took the form of thrusting from the south northward, accompanied by profound crustal shortening.[15] The first effect was the formation of the core of the Ouachita anticlinorium, the axis of which had a strike slightly north of east. This was probably accompanied by major thrust-faulting in the Athens Plateau.

As the push from the south continued, the whole Ouachita segment was thrust northward. The western end dragged against the buttress formed by the Arbuckle Mountains and produced an arcuate structural salient already described.[16] The eastern end dragged against a buttress concealed beneath the Gulf Coastal Plain of southeastern Arkansas, probably the buried igneous masses encountered by drilling near Lake Village (Fig. 1). But instead of forming an arcuate structural salient here, the backbone of the anticlinorium buckled so that it now shows an abrupt change in strike from N. 75° E. to S. 65° E.

Fig. 4, a photograph[17] of a relief model prepared by the Arkansas Geological Survey, helps to visualize the history of the deformation. The Novaculite ridges, because they best indicate the structural pattern of the Ouachita Uplift, are painted black.

The distribution and attitude of the Novaculite outcrops indicate a somewhat complicated diastrophic sequence. The outcrops at *A* (Fig. 4) indicate the formation of the initial core of the anti-

[15] Dake, C. L.: The Problem of the St. Peter Sandstone. Bull. Missouri Univ. Sch. of Mines and Met. vol. 6, no. 1, 1921; Powers, S.: Age of Folding of Oklahoma Mountains. Bull. Geol. Soc. Amer. vol. 39, pp. 1031–1072, 1928; Honess, C. W.: Geology of the Southern Ouachita Mountains of Oklahoma. Okla. Geol. Survey, Bull. 32, 1923.

[16] Miser, H. D.: Structure of the Ouachita Mountains of Oklahoma and Arkansas. Okla. Geol. Survey, Bull. 50, 1929.

[17] Courtesy of George C. Branner, State Geologist.

clinorium. Those at *B*, which comprise the Zigzag Mountains around Hot Springs, indicate east-west shortening of the south limb produced by major cross-buckling, the axis of which is along the X–Y line. After the east-west stress had been relieved, the

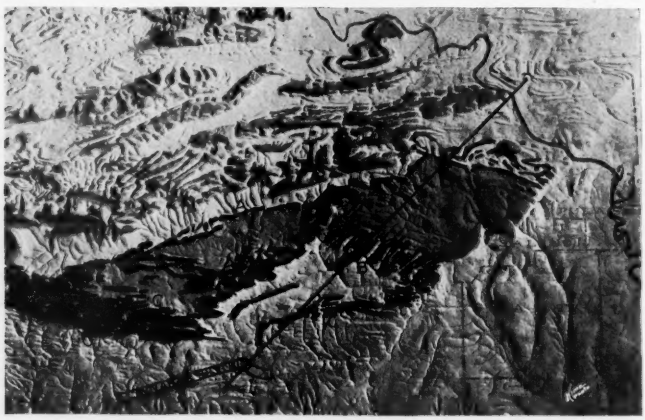


FIG. 4. Photograph of relief model, showing structural pattern of the Ouachita Mountains as expressed by the Arkansas Novaculite. *A*, north-south folding; *B*, east-west buckling along axis X–Y; *C*, north-south folding. (Courtesy of Arkansas Geol. Survey.)

push from the south, probably continuous throughout the buckling period, continued to exert itself, forming the folds at *C*. Thus the thrusting from the south may be considered to have suffered an intermediate period of intense buckling that produced much east-west shortening, followed by a continuation of the north-south shortening already recognized in connection with the formation of the Ouachita Uplift.

The amount of north-south shortening has been estimated to be 60 miles.[18] It is as yet impossible to estimate the total east-west shortening, but the shortening shown by the Gap Ridge member of the Stanley shale in Fig. 3 amounts to about 3⅓ miles in 12. In a straight-line distance of 62,800 feet the length of

[18] Reference, footnote 15.

the marker horizon is approximately 80,200 feet, a difference of 17,400 feet.

Most of the cinnabar district lies west of the axis of buckling, but the area near Antoine Creek, which runs along that major structural disturbance mapped as the Amity fault, is just at the axis. This may explain the profound deformation as well as the change in strike of the east end of the cinnabar district, the details of which have not yet been worked out.

During the period of buckling, the already partially up-ended beds in the cinnabar district were subjected to east-west shortening which produced cross-folding and faulting. Especially susceptible to the east-west stresses were the Stanley and Jackfork facies which lay along the south edge of the regional thrust fault. Fig. 3 shows the pattern of this deformation. Most of the cross-faulting is along planes striking N. 20° to 30° E. Complementary faults striking about N. 20° W. are also present, but not common. Axes of the cross folds are mostly about N. 25° E. During and after the period of yielding to the east-west stress, the continued thrusting from the south seems to have pushed northward along the thust-fault plane irregular segments of the crumpled formations which lay along its south edge. At this time the steep southward dip of the up-ended beds may have been increased to the present nearly vertical attitude.

With this picture of the north-south thrusting and east-west buckling in mind it is possible to understand the local structural features controlling the cinnabar deposition.

ORE OCCURRENCE.

The cinnabar has four modes of occurrence. In their order of importance they are: (1) fracture and breccia filling; (2) fault gouge and shale contact impregnation; (3) vein material; (4) local dissemination in sandstone (negligible).

The most important mode of occurrence is that of fracture filling, but this is very erratic. Generally there is not sufficient cinnabar to saturate the fractures in any one locality over any extended zone. However, the fractures which seem most hospitable can be classified for exploration purposes.

FRACTURE SYSTEMS.

Three dominant sets of fractures occur in the district, complicated by many shatter cracks that defy general classification:

1. A system with nearly horizontal attitude or with dips of 10° to 20° either east or west, and with strikes normal to the bedding. These fractures were probably developed during the north-south shortening that up-ended the beds, and are complementary to the bedding planes.

2. A system striking N. 4° to 30° E. and dipping from 60° to vertical.

3. A system striking N. 10° to 20° W. and dipping from 75° to vertical. These are complementary to those in System 2 and were probably developed during the east-west shortening period.

Fractures belonging to System 1 are found to interrupt and offset fractures belonging to systems 2 and 3, and vice-versa, so that it seems possible that System 1 fractures developed both before and after those of Systems 2 and 3. Systems 2 and 3 are much more abundant than System 1. Mineralization is rarely found in System 1. In fact, fractures belonging to System 1 have been observed to cut off mineralization in fractures of System 2.

Single fractures belonging to Systems 2 and 3 are habitually discontinuous from bed to bed, although rarely they cut a thick series of beds, and fracture zones that cut several beds are common.

GAP RIDGE MINE.

Gap Ridge Mine is the best example of a commercial ore body formed by fracture-filling deposition. It lies near the crest, on the south slope of a narrow ridge that rises 180 feet above the valley bottom. Situated ¾ mile west of the nearest major cross-fault, and ¼ mile south of the outcrop of the regional thrust-fault (Fig. 3) the beds show little deformation aside from having been up-ended.

The mine is in massive sandstone beds that occur at the top of the lower sandstone phase of the Gap Ridge member of the

Stanley Shale. Figure 5 shows a longitudinal section looking southward at the hanging wall, together with a plan view section showing the stratigraphy at the 120 foot level. The section from hanging wall to foot wall is:

Rock	*Thickness*		
1. Shale	Indefinite (100 feet)		
2. Sandstone	6 inches	Hanging Wall	4 feet
Knife edge contact			
3. Sandstone	20 inches		
Knife edge contact			
4. Sandsone	20 inches		
5. Shale	½ inch	Stope	8 feet
6. Sandstone	8 inches		
Knife edge contact			
7. Sandstone	54 inches		
8. Shale	2 inches		
9. Sandstone	8 inches		
Knife edge contact			
10. Sandstone	12 inches		
11. Sandstone	14 inches		
12. Sandstone	78 inches—Footwall		6½ feet

From Bed 1 to Bed 11, all the beds are mineralized along fractures that strike N. 8° to 10° E. and dip approximately 75° W., belonging to System 2. Near Bed 1, north-south displacement amounting to as much as 10 inches has taken place along these fractures, but the magnitude of the displacement dies out toward the footwall and the fractures themselves terminate abruptly against Bed 11. The footwall is undistorted; the rare fractures in it belong to Systems 1 and 3.

The outer 4 feet of sandstone beds, although mineralized, have been left to form the hanging wall as a buttress against the shale. For a distance of about 70 feet along the strike of the ore beds, major fractures occur at oddly spaced intervals, averaging about 6 feet. Between these major fractures, minor fracturing and shattering undoubtedly form connecting channels. Fig. 5 outlines the mine opening that generally bounds the ore body. It is

notable that, although the fractures dip steeply westward, the ore body itself seems to be vertical. Fractures that are mineralized at the surface become barren in depth to the westward, and frac-

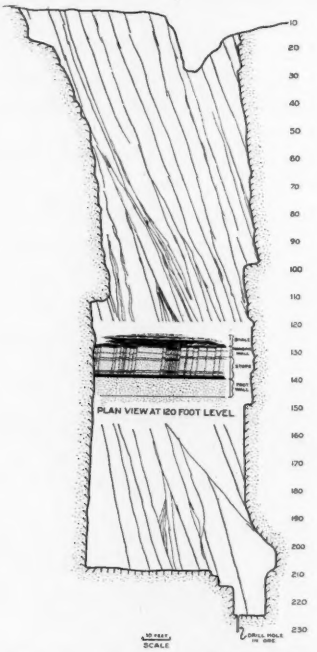


FIG. 5. Longitudinal section of Gap Ridge Mine looking S. toward hanging wall, showing principal fractures. The plan view at the 120-foot level shows how the fractures die against the footwall.

tures mineralized at depth are barren at the surface where they outcrop too far east. No definite reason has been found for the east and west boundaries of the ore body.

The Gap Ridge Mine is an open stope averaging 7 feet in width, varying in length from 12 to 80 feet, and 225 feet deep. It has produced approximately 5,980 tons of rock, of which 2,250 tons was ore having a quicksilver content averaging 22 pounds per ton,

and 3,730 tons was waste or lower grade ore. The average ratio of 22-pound ore to discarded rock for the upper half of the stope was 1 to 1.86; for the lower half, 1 to 1.4; for the entire stope, 1 to 1.66. If it had not been necessary to remove the footwall shale the ratio of ore to rock in place would have been 1 to 1.15.

The quicksilver content of the total rock removed averaged about 8.28 pounds per ton, not including the cinnabar content of the lean ore discarded with the waste, which would probably bring the average up to about 10 pounds per ton. The ore seems slightly richer with depth.

Fig. 6 [19] shows a typical specimen of ore from the Gap Ridge Mine, taken from the shattered zone near the middle of the stope at the 120-foot level. This illustrates the fracture-filling type of ore occurrence. The tenor of such a specimen is about 50 pounds of metallic mercury per ton.

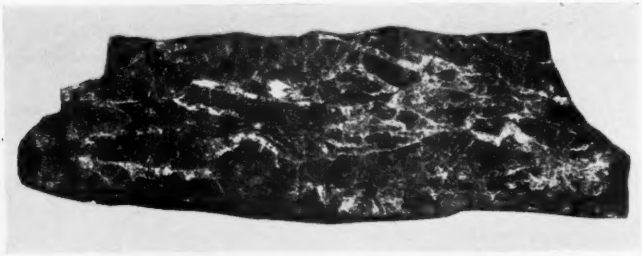


FIG. 6. Fracture-filling type of ore from Gap Ridge Mine. White, dickite; light gray, cinnabar; dark gray, quartzite. Length of specimen, 35 cm.

PARKER HILL MINE.

Parker Hill mine offers an example of the vein and fault gouge modes of cinnabar occurrence, in combination with fracture filling. It also best illustrates the relationship between regional structure and ore deposition. The hill itself is a small elongated dome-shaped knob about 600 feet long and 350 feet across, which rises 105 feet above the valley floor. It is composed of a sand-

[19] Photograph by H. L. Koch, Washington University, St. Louis, Mo.

stone series in the Stanley Shale, having a total thickness of less than 200 feet, and called the Parker Hill member. The beds are vertical.

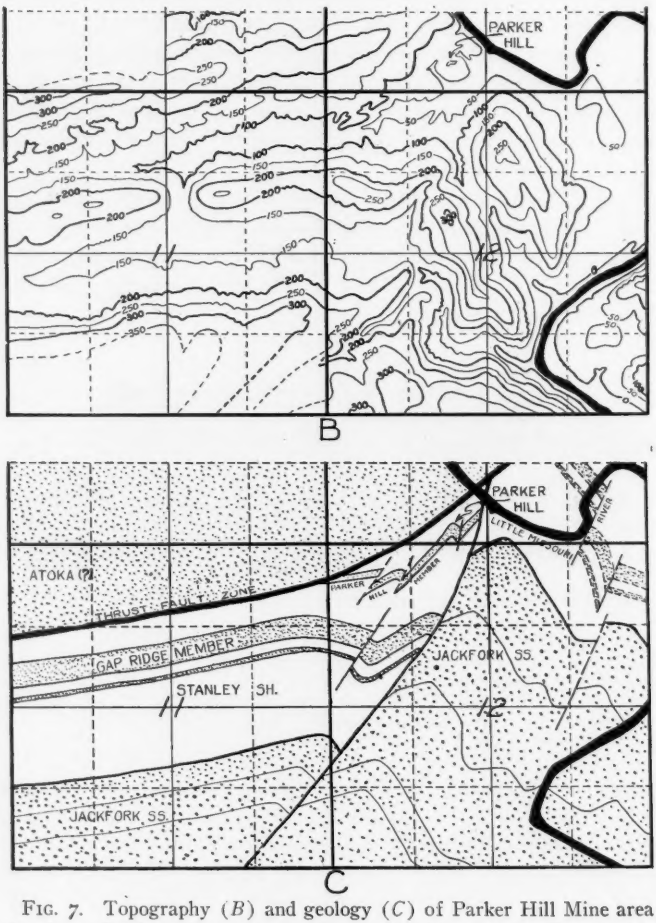


FIG. 7. Topography (*B*) and geology (*C*) of Parker Hill Mine area; showing reflection of structure in the topographic pattern. Datum plane is low-water level of Little Missouri River.

As shown in Fig. 7, the Parker Hill mine lies less than 200 feet southeast of the regional thrust fault and west of a major cross fault along which the Jackfork has been thrust northward nearly 4,000 feet at the west nose of a cross buckle that changes the regional strike from N. 80° E. to S. 30° E. The structure of the hill is a broken drag fold, the east limb of which has cracked and thrust northward, westward, and upward along a plane which strikes N. 4° E. and dips 58° eastward.

Ore Occurrence.—A trench into the southwest slope of the hill at the point where the original specimen was found discloses the intense shattering in the sandstone which would be expected to accompany the sharp turn in the cross fold. Through this shattered sandstone runs a distinct vein which strikes about N. 4° E. and dips about 55° E. It varies in thickness from 1 to 4 inches, and in content from nearly pure cinnabar to nearly pure gangue material, quartz and dickite. An average sample yielded 10.67 per cent. metallic mercury, or 213 pounds per ton. The vein is probably along a minor fault similar to the one at the east side of the hill.

Trench No. 2 was driven along the footwall of the east cross-fault, the horizontal component of displacement of which is about 8 feet, the stratigraphic section east of the fault being found 8 feet farther north than that on the west side. In places, this fault was sealed with solid cinnabar, and the clay gouge along it contained 60 pounds of mercury per ton of ore. West of the fault, the fractures in the sandstone are mineralized over distances varying from one to ten feet from the fault. The ore from this fracture zone was sorted to a tenor of 20 to 30 pounds per ton. Fractures immediately east of the fault were barren. About 50 feet into the hillside, the cut encountered first a 5-foot shale bed (hanging wall), then 10 feet of sandstone beds 2 to 5 feet in thickness (ore zone), and finally a massive 14-foot sandstone bed (footwall). Where the fault encounters the footwall, the metallization is not economic. In the beds between it and the shale, however, the fractures are mineralized at least 60 feet westward from the fault.

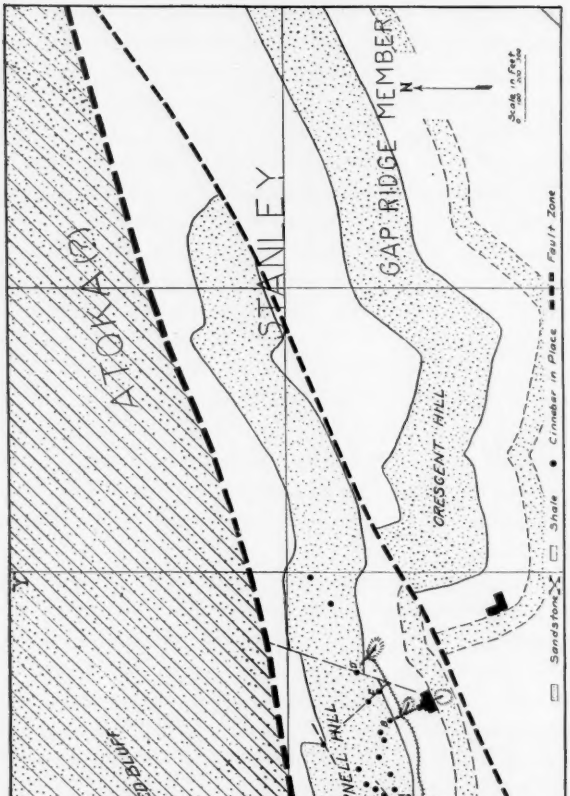


FIG. 8. Geology of Parnell Hill, with structural section and magnetic profile along line X–Y.

Trench No. 3 was driven into the hill about 70 feet west of No. 2, in order to encounter the ore beds where they round the nose of the crossfold. It shows well mineralized fractures, which yield sorted ore of about 20 pounds of quicksilver per ton. A shaft sunk to a depth of 120 feet, between the nose of the fold and the thrust fault, disclosed sortable ore all the way. At a depth of 112 feet a drift was run west, entirely in ore, along the ore bed to the nose of the fold, a distance of 35 feet.

At the Parker Hill mine about 4,000 tons of rock has been moved, of which 850 tons was ore averaging 22 pounds of quicksilver per ton, 1,800 tons was stripping, and 1,350 tons was discarded waste and lean ore. Thus the ratio of ore to total rock moved is 1 to 4.7. The ratio of ore to waste in the ore body is 1 to 1.6, but this includes more waste than normal, owing to cave-in rock.

PARNELL HILL.

"Shale ore" in commercial quantities has been found on Parnell Hill. The structure of this area[20] is shown in Fig. 8.

Near the middle of the hill (*A*, Fig. 8) a sharp cross-fold buckles the Gap Ridge sandstone member of the Stanley Shale. Fig. 9 shows details of deformation at the contact of the lower sandstone phase of the Gap Ridge member with the middle shale phase. This is the same horizon in which Gap Ridge mine is developed. The drag of the sandstone beds against the shale as folding progressed separated the sandstone layers along their shale partings, permitting the mineralization of the shale intercalations. Ore has been taken out of this nose to a depth of 70 feet below the outcrop.

About 300 feet east of this fold, a trench driven northward into the hill encountered a 14-inch layer of mixed shale and cinnabar which is the richest occurrence of the district. It was found about 50 feet stratigraphically below the contact of the shale and sandstone of the Gap Ridge member, where a shaly zone overlies a massive quartzite bed. The thickness of the ore is very erratic

[20] Stearn, N. H.: Mining and Furnacing Quicksilver Ore. Eng. and Min. Jour., vol. 134, pp. 22–24, 1933.

east and west and with depth, but it persists over 122 feet below the outcrop. The presence of this ore is attributed to the separation of the shaly zone from the footwall brought about by movement along it, producing an incipient drag fold. This permitted

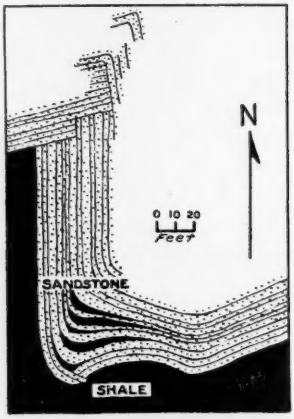


FIG. 9. Details of the cross fold at *A*, Fig. 8, Parnell Hill.

ingress of the mineralizing solutions, which deposited cinnabar wherever the shale was not too tightly pressed against the quartzite. Movement in the shale bed which permitted the mineralization has almost made a gouge of the original shale bed.

Summary of Ore Occurrence.

The occurrence of the ore at Gap Ridge, Parker Hill, and Parnell Hill is responsible for the theory that metallizing solutions made their way along the thrust fault that outcrops north of them and cuts under them, and into overlying fractured zones. The sandstone formations were sufficiently competent to maintain open fractures, so that they were the preferred hosts for metallization. Thus, ore deposits are found in the Parker Hill and Gap Ridge members of the Stanley, and occasionally in the Jackfork sandstone farther south.

Within the sandstone formations, those beds which were adjacent to shale horizons were shattered and moved more extensively than others, so that they are locally the preferred hosts for metallization. This accounts for the development of ore bodies near the shale contacts. It is possible, too, that at the time of metallization the beds were dipping steeply southward instead of standing vertically, so that the shale horizons offered impervious obstructions to the rising solutions. This would also account for the cinnabar concentrations near the shale contacts, even though the beds now are nearly vertical, having been completely up-ended by further thrusting subsequent to the metallization.

The ore bodies are not extensive in area but seem to be persistent vertically; their tenor varies up to 200 pounds of metallic mercury per ton of ore. By careful prospecting, using geological guides, a fair grade of ore can be developed. The average tenor of the total tonnage run through the plant of the Southwestern Quicksilver Co. is 23.4 pounds of metallic mercury per ton. The ratio of ore to rock moved throughout the total development operations, including all exploration trenching, test pitting and stripping, is about 1 to 3.5. Thus, the average tenor of the total rock moved is 5.2 pounds of metallic mercury per ton.

Character of Ore.

The ore consists of a gangue of quartzitic sandstone, distorted shale, or fault gouge, in the voids of which occur dickite, cinnabar, and vein quartz, with almost negligible amounts of accessory minerals.

A list of the minerals (exclusive of those indigenous to the country rock) [21] in the order of their abundance includes: (1) dickite, (2) quartz, (3) iron oxide, (4) cinnabar, (5) pyrite, (6) stibnite, (7) native mercury, (8) siderite, (9) opal, (10) metacinnabar, (11) eglestonite, (12) livingstonite, (13) calomel, (14) stibiconite.

[21] For a description of country rock minerals see Sohlberg, R. H.: Cinnabar and Associated Minerals from Pike County, Arkansas. Amer. Miner., vol. 18, no. 1, 1933.

Dickite is the dominant mineral in the district. Normally powdery white with a talcy feel, it is commonly stained yellow to brown by iron oxide. It is a guide mineral to the ore zones. The ore is always associated with dickite, but there are many occurrences of dickite without ore. Being more resistant to decomposition than the cinnabar, it is much more wide-spread at the surface, where casts in it indicate the former presence of cinnabar.

The *cinnabar* is generally coarsely crystalline, ⅞ inch crystals being observed. The crystals are normally twinned with double rhombohedral penetration twins. The cinnabar, where fresh, is generally semi-translucent and bright vermilion to crimson-red in color. It is intimately intermixed with the dickite, probably having crystallized almost simultaneously. Perfect double-terminated crystals of cinnabar are commonly found entirely surrounded by dickite.

The associated *quartz* is of three varieties—milky quartz, smoky quartz, and glassy quartz crystals, and may indicate three different phases of crystallization. The milky quartz generally adheres to the wall rock, and, according to Sohlberg,[22] is partially replaced by dickite and in places surrounded by cinnabar. The smoky quartz is intimately intergrown with dickite and cinnabar, and appears to have crystallized about the same time. It is probably discolored by local inclusions. The clear quartz may be of the same generation as the dark, but crystals of it contain stibnite and cinnabar inclusions;[23] these inclusions suggest crystallization later than the cinnabar. However, some of the quartz crystals are completely surrounded by dickite, suggesting that the development of the smoky quartz, clear quartz, cinnabar, and dickite was nearly simultaneous.

The pronounced *iron oxide* staining on the surface is probably all secondary after pyrite and siderite. It varies in color from black through scarlet to pale yellow, and in texture from massive to earthy ocher. The scarlet iron oxide is frequently mistaken for cinnabar.

Pyrite is uncommon and in small amount. It occurs in two

[22] Reference, footnote 21.

[23] Stearn, N. H.: Stibnite in Quartz. Amer. Miner. vol. 20, no. 1, p. 59, 1935.

varieties:—(1) small, irregular masses of sugary pyrite, which were probably originally present in the dark shales of the country rock, particularly the carbonaceous ones; (2) a late variety in the form of small cubic crystals that line vugs and coat crystals of clear quartz. The latter is thought to be auriferous, a sample of pyritiferous rock having assayed 0.02 ounces of gold and 0.4 ounces of silver to the ton. The same assay showed a small amount of arsenic, indicating the presence of arsenic minerals, which, however, have not been identified.

Stibnite occurs in small amounts at Parnell Hill near the surface, and at Gap Ridge about 180 feet below the surface. It has been noted in shale gouge, in distorted acicular crystals; in open fractures with the bladed crystals at right angles to the walls and bent by movement along them; and plastered on fracture walls, in radiating rosettes. Within the masses of stibnite, crystals of cinnabar are common. Cinnabar, quartz (chalcedony or opal) and dickite all replace and are pseudomorphous after stibnite, which, therefore, must have been formed before the main metallization. Rarely, inclusions of stibnite are observed in cinnabar

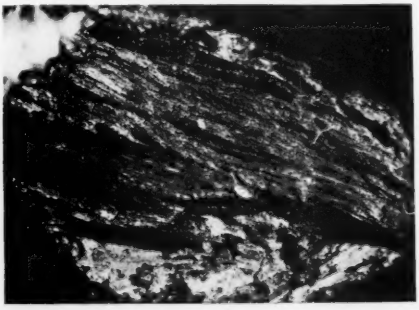


FIG. 10. Cinnabar pseudomorphous after stibnite, Parnell Hill Mine. × 10.

crystals. Fig. 10[19] shows cinnabar pseudomorphous after stibnite from Parnell Hill Mine.

Some *siderite*[24] was found at a depth of about 120 feet in Gap Ridge, near a shale-sandstone contact, surrounding fragments of a brecciated rock, followed by massive dickite. The siderite layer shows crystal terminations, indicating deposition in open space; these are covered by dickite, indicating its later development. A similar occurrence was observed from Parker Hill, where siderite appeared to be replaced by dickite.

Surface alteration throughout the oxide zone has produced an interesting array of secondary minerals of no importance. The dickite has escaped alteration. The cinnabar is altered to *metacinnabar, native mercury, eglestonite,*[25] *livingstonite,*[26] and *calomel.* The quartz becomes *chalcedony* or *opal.* The pyrite and siderite change to hydrated *iron oxide,* and the stibnite to *stibiconite.*[25]

Fig. 11 represents the sequence of development of the observed minerals from field observations. Their interrelationship suggests that there were two and perhaps three phases of mineralization, which may have been separated by time intervals or may have been rhythms of the same mineralization period. During the first phase quartz, stibnite, and siderite crystallized against the country rock. During the second, dickite, cinnabar, and quartz crystallized into intimate intermixtures. The third may have resulted in auriferous pyrite and more quartz, but this is less well defined than the other two.

Oxidation produced striking, but minor alterations. Cinnabar was removed from the dickite near the surface, and some secondary metallic mercury was formed. One specimen, from a depth of 112 feet in the Parker Hill Mine, shows the alteration of cinnabar crystals into metallic mercury which forms globules in craterlike pits in the cinnabar crystals.

ORIGIN.

The association of the cinnabar with dickite and auriferous pyrite is considered to prove a hydrothermal origin, but no evi-

[24] Field identification checked by Dr. W. O. Shipton, Dr. Carl Tolman, and M. G. Dings, Washington University, St. Louis, Mo.

[25] First identified by F. H. Pough, Washington University, St. Louis, Mo.

[26] First identified by R. G. Sohlberg, *op. cit.*

dence of igneous activity has been found in the district, other than the mineralization itself. Near Murfreesboro, 9 miles south, there is a small peridotite plug; 14 miles north, near Caddo Gap, there are warm springs; 21 miles west, an ouachitite dike is re-

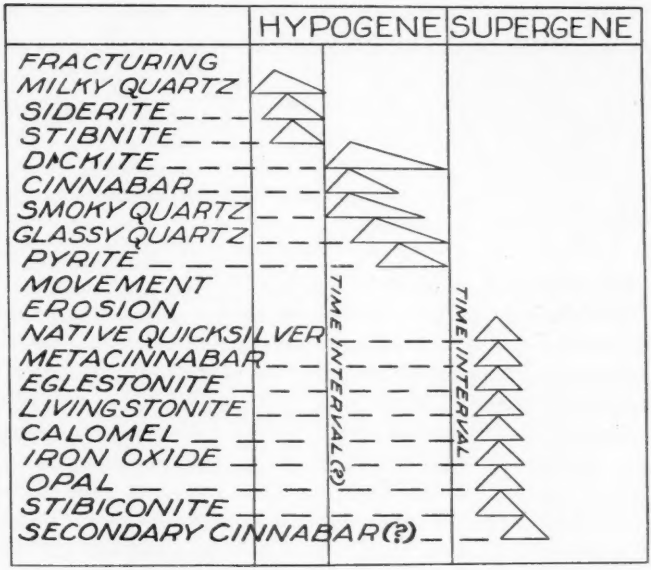


FIG. 11. Inferred mineral sequence of the district.

ported; 32 miles northeast are the hot springs and dikes in and near the Zigzag Mountains of Hot Springs; and 16 miles south, in the Cretaceous Overlap, are beds of acidic tuffs and conglomerates. Thus the district is surrounded by indications of igneous activity, none of which is sufficiently closely related to it to be considered as a source. The source is, therefore, assumed to be an unexposed igneous body which may or may not be directly related to the igneous phenomena that have reached the surface.

Of the phenomena enumerated above, the age of only two has

been definitely reported; *i.e.*, the peridotite near Murfreesboro [27] and the acidic tuffs and agglomerates near Centerpoint,[28] both of which have been assigned to early Upper Cretaceous. All that can definitely be said of the other igneous phenomena of the Ouachita Uplift is that they are later than the initiation of the mountain-making movements, or post-Middle Pennsylvanian. It cannot even be said that the various igneous phenomena all belong to the same age.

The metallization in the cinnabar district occurred after the buckling period which produced the crossfolds, faults, and fractures that controlled the deposition, and there is some evidence that it may have been completed before the subsequent mountain-making movements subsided.

At Parker Hill are extensive slickensided surfaces that cut and polish previously mineralized fractures. Movement of a magnitude greater than that of ordinary settling is indicated by the degree of polish on the resistant quartzites, and the striations, in so far as they can be considered indicative, suggest that it was a thrust movement. Cinnabar has been polished by these slickensides, and is also in undisturbed crystals on slickensided surfaces. This indicates, (a) that the fracture was formed during the metallization period; (b) that there might have been two periods of mineralization; or (c) that redeposition of supergene cinnabar has taken place. Because this evidence came from near the surface at Parker Hill, it was given little weight until similar evidence was found at a depth of about 150 feet at Gap Ridge where the regional distortion is much less extreme than at Parker Hill.

After the mountain-building movements that produced the Ouachita Uplift were complete, no major disturbances are known to have occurred in this area. It therefore seems possible that the metallization took place during the mountain-building movements

[27] Miser, H. D. and Ross, C. S.: Diamond-bearing Peridotite in Pike County, Arkansas. U. S. Geol. Survey, Bull. 735, pp. 311–312, 1923.

[28] Ross, C. S., Miser, H. D., and Stephenson, L. W.: Water-laid Volcanic Rocks of Early Upper Cretaceous Age in Southwestern Arkansas, Southeastern Oklahoma, and Northeastern Texas. U. S. Geol. Survey, Prof. Paper 154, 1928.

of Pennsylvanian time. This is in harmony with the opinion of Honess as quoted by Branner,[29] with regard to the age of the sulphide deposits in the Ouachita Mountains of Oklahoma, the occurrence of which[30] has points of resemblance to that of the cinnabar in Arkansas.

SUMMARY.

The cinnabar district in southwestern Arkansas is nearly 30 miles long and less than two miles wide. Exploration activity began at both ends of the district in August, 1931. Exploration in the west end, dominated by the Southwestern Quicksilver Co., was accompanied by detailed geological examination. No extensive detailed geological surveying was done in the east end, so that details of structure and ore occurrence have not as yet been worked out there.

The district lies on the Athens Plateau between the Ouachita Mountains and the Cretaceous Overlap. Rocks assumed to be equivalent to the Stanley, Jackfork, and Atoka formations of Oklahoma are the country rocks. The formations have been folded to a vertical position, faulted so that Upper Stanley is brought into superposition upon Atoka (?) by thrusting from the south, and buckled by east-west shortening which caused cross-faults and folds.

Most of the ore deposits are found in sandstone members of the Stanley and Jackfork south of the regional thrust fault and near the cross-faults or folds caused by the east-west shortening. The theory is that mineralized solutions worked their way up the major fault and rose through the shattered zones produced by the buckling in the sandstone horizons.

The ores are mainly fracture fillings in the sandstone, with dickite, cinnabar and quartz as the principal minerals. The ores are of hydrothermal origin and may have formed during the mountain building of late Pennsylvanian time.

The tenor of the ore in place is about 10 pounds of metallic

[29] Reference, footnote 1, p. 28.

[30] Honess, C. W.: Geology of the Southern Ouachita Mountains of Oklahoma, part II, Geography and Economic Geology. Okla. Geol. Survey, Bull. 32, 1923.

mercury to the ton of rock, but this is hand sorted to yield about 24 pounds per ton. The ratio of ore of this tenor to waste averages about 1 to 1.6, not counting surface stripping. The maximum vertical development in the district to date is 225 feet, at Gap Ridge Mine. Little change in the habit, characteristics or tenor of the ore is noted with depth, except that it appears to become slightly richer.

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THE HYDROTHERMAL OXIDATION OF MANGANESE MINERALS.

S. A. TRENGOVE.

INTRODUCTION.

THE well known association of the oxides of iron and manganese in ore deposits leads to new speculation upon the origin of either of them when a new theory is advanced for the origin of the other. Thus, soon after the demonstration by Gruner [1] that steam alone oxidizes certain iron minerals at comparatively low temperatures in a few hours' time, data of a comparative nature were sought for manganese minerals. About two hundred hydrothermal oxidation experiments were made. The results of these, together with certain published field data, indicate that steam alone may be the principal source of oxygen in the genesis of certain manganese oxide deposits.

The writer wishes to thank Dr. J. W. Gruner for many helpful suggestions and criticisms, both during the laboratory studies and during the preparation of this paper. Professors P. Christianson and L. B. Pease of the Minnesota School of Mines have also aided in many ways.

PREVIOUS WORK.

Oxidation and decomposition experiments on manganese minerals have been performed by a number of investigators. L. Joulin [2] measured the CO_2 pressure (215 mm. of mercury) developed by heating manganous carbonate in a bomb to 150° C. On cooling, the pressure slowly returned to its initial value, indicating strong reabsorption of the gas. Above 200° C. the dissociation was permanent. Mellor [3] points out that CO_2 may be

[1] Gruner, J. W.: Hydrothermal Oxidation and Leaching Experiments. ECON. GEOL., vol. 25, pp. 697–719, 837–867, 1930.

[2] Joulin, L.: Ann. Chem. Phys., (4) vol. 30, p. 248, 1873.

[3] Mellor, J. W.: A Comprehensive Treatise on Inorganic and Theoretical Chemistry, vol. 12, p. 435, Longmans Green & Co., 1932.

reduced by manganous oxide, involving a complex series of reactions.

The results obtained by Joulin on artificial manganous carbonate have been in part confirmed by Manchot and Lorenz.[4] They further proved that increased water content of the material used was accompanied by increased pressure of dissociation. They found it impossible to duplicate results at any given temperature unless the water content was the same. In the course of their experiments it developed that artificial anhydrous manganous carbonate was very difficult, if not impossible, to obtain. Using natural rhodochrosite, which is anhydrous, they found much lower dissociation pressures for any given temperatures.

M. Berthelot and others [5] have investigated the theoretical heats of formation of various manganous carbonates and have shown that the natural rhodochrosite is more stable than the artificial.

Friedrich and Smith [6] have shown in the case of natural rhodochrosite that iron carbonate, when present, as is almost always the case, tends to lower the resistance to dissociation. Carbonates of calcium and magnesium, on the other hand, tend to increase this resistance. Grünberg's experiments [7] on natural carbonates confirmed the above statements. Grünberg's work also showed that an air-free CO_2 atmosphere has a retarding effect on the dissociation of carbonates, whereas moisture, when present, accelerates the dissociation. Mellor [8] mentions a number of investigations which have shown that heating manganous carbonate in air with water vapor or in oxygen with water vapor produces strong oxidation in a few hours at 200° C.

EXPERIMENTAL WORK.

Materials Used.—No. 1 rhodochrosite used for the greater portion of these experiments, is a powdered (— 200 mesh) natural rhodochrosite from an unknown locality (Table I).

[4] Manchot, W., and Lorenz, L.: Zeit. Anorg. Chem., vol. 134, p. 297, 1924.
[5] Mellor, J. W.: *Op. cit.*, p. 436.
[6] Friedrich, K., and Smith, L. G.: Centralb. für Miner., 1912, pp. 615, 651, 688.
[7] Grünberg, K.: Zeit. Anorg. Chem., vol. 80, p. 337, 1913.
[8] *Op. cit.*, p. 437.

TABLE I.

RHODOCHROSITE.

Number.	$MnCO_3$.	$FeCO_3$.	SiO_2.	$MgCO_3$.	MnO_2.	Total.
1	89.95	1.50	2.16	6.03	None	99.64
2	90.23	3.56	1.96	4.02	"	99.77
3	89.01	3.03	2.71	4.88	"	99.63
4	87.32	2.87	1.98	7.63	"	99.80
5	82.01	7.86	4.88	[a]	"	—

[a] Not determined; probably chiefly $MgCO_3$ makes up the remainder of the material.

TABLE II.

OXIDATION OF RHODOCHROSITE NO. 1 IN A CONTINUOUS FLOW OF STEAM AT ATMOSPHERIC PRESSURE. TIME:—24 HOURS.

Exper. No.	Temp. ° C.	Per cent MnO_2 after expt.	Per cent of MnO converted to MnO_2.	Exper. No.	Temp. ° C.	Per cent MnO_2 after expt.	Per cent of MnO converted to MnO_2.
7	150	None	—	32	280	10.57	8.33
				33	280	10.91	8.60
18	170	Trace	Tr.	34	280	10.10	7.95
19	170	None	—	35	280	10.52	8.28
20	170	Trace	Tr.				
				36	300	11.68	9.25
14	175	0.35	0.29	37	300	13.27	10.37
15	175	0.29	0.24	38	300	12.01	9.42
21	180	0.60	0.49	44	310	11.48	9.00
22	180	0.51	0.42				
				42	315	12.20	9.55
23	190	0.93	0.76	43	315	11.65	9.12
24	190	0.88	0.75				
				39	325	10.98	8.65
5	200	1.21	0.99	40	325	11.75	9.20
6	200	1.17	0.95	41	325	11.27	8.82
25	215	2.37	1.92	45	340	10.99	8.66
26	215	2.45	1.98	46	340	11.50	9.00
27	230	3.36	2.71	47	350	11.37	8.90
28	230	3.81	3.07	48	350	11.78	9.22
29	230	3.43	2.77				
				49	375	12.20	9.55
2	250	6.24	4.98	50	375	13.32	10.42
3	250	5.13	4.12	51	375	12.50	9.79
4	250	6.09	4.87				
				52	400	13.30	10.41
30	265	8.27	6.57	53	400	13.41	10.51
31	265	8.20	6.52				

No. 2 rhodochrosite is from Lake County, Colorado; No. 3, from Philipsburg, Montana; No. 4, from Butte, Montana; No. 5, from the Cuyuna Range, Minnesota. Rhodochrosite specimens Nos. 2 to 5 were used in grains of about ¼ inch in diameter. Artificial manganous carbonate was not used in these experiments, for reasons pointed out above. No. 6 rhodonite is from Butte, Montana. It contains from 5 per cent. to 10 per cent. $MnCO_3$ but no MnO_2. Used in ¼ inch grains. No. 7 fowlerite is from Franklin Furnace, New Jersey. The specimens analysed showed no trace of carbonate or MnO_2. Used in grains ¼ inch in diameter.

Apparatus.—The apparatus used in making all the atmospheric-pressure hydrothermal oxidation experiments recorded in this paper has been described by Park.[9] However, certain improvements and additions were made. The furnace was constructed in two parts, with a space of about two inches between them, and peep-tubes were placed in this space (Fig. 1). With this arrangement the color changes taking place could easily be observed. All rubber connections were eliminated where they would be subjected to heating effects, and fused connections or ground glass joints were substituted. An 8-liter vessel was used as a collector for the condensed water. At the beginning of the experiments this vessel was filled with boiled water to help in removing air from the apparatus. This water was then partly syphoned off under pressure of the nitrogen stream described below. "Medical" and (in part) commercial nitrogen was used as "atmosphere" for most of the experiments. The oxygen in this gas was removed by passing over yellow stick phosphorus. At the beginning of the experiments a nitrogen stream was passed through the apparatus for about four hours until the furnace could be brought to a steady temperature. After that the nitrogen was passed through very slowly at the rate of 2 or 3 bubbles per minute. Gas tests made in standard gas-testing apparatus after the first three hours failed to show any evidence of oxygen

[9] Park, Charles F., Jr.: Hydrothermal Experiments with Copper Compounds. Econ. Geol., vol. 26, p. 859, 1931.

in the gas collector.[10] All water used in these experiments was boiled for at least ten minutes before syphoning it into the main boiler. Temperature control for these experiments was obtained through the use of Wilson-Maeulen regulator, using chromel-

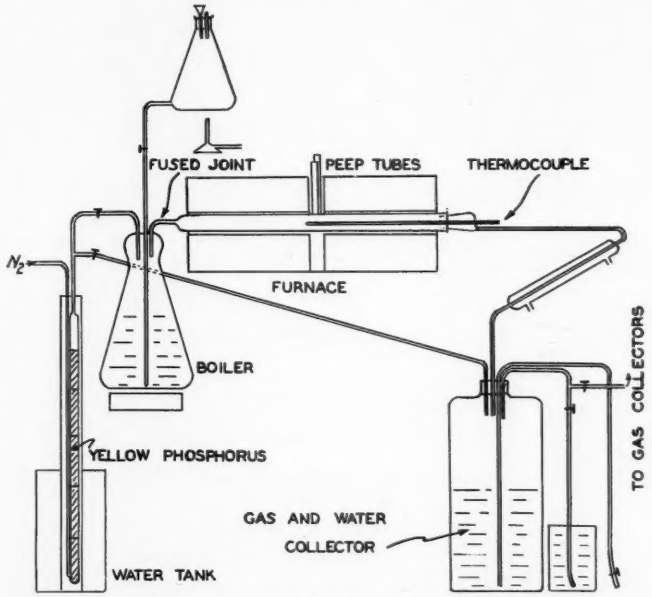

FIG. 1. Furnace for experiments at atmospheric pressure.

alumel thermocouples and Leeds-Northrup potentiometers for checking. The maximum temperature variation was $\pm 5°$ C. In all but the bomb experiments and some of the special experiments mineral samples of about two grams each were used. Check experiments in which the weight of sample was varied showed percentage results similar to those of the two-gram samples. Clean porcelain boats were used for all tests.

In the bomb experiments, apparatus like that described by

[10] Methods for the Technical Sampling and Analysis of Gases. U. S. Steel Corporation, 1918.

Gruner [11] was used. In this type of bomb the gases escape very slowly through a special valve while at the same time a high pressure is maintained. Air was displaced from the bombs by dropping in a few small pieces of solid CO_2. The bomb was covered with a piece of annealed gold sheet as soon as the air had been expelled. The steel cover was fastened while this gold sheet still vibrated from the force of the escaping CO_2.

Detection of Hydrogen in the Exhaustive Gases.

The apparatus used was the same as for all other atmospheric pressure experiments, with the following absorption train connected to the gas collector to receive exhaust gases: (1) Calcium chloride dryer. (2) Askarite absorber for CO_2. (3) Bromine water for phosphorous compounds and (?) hydrocarbons. (4) Alkaline pyrogallate absorbers for oxygen. These also remove bromine fumes. (5) Ammoniacal cuprous chloride for CO. (6) Calcium chloride dryer. (7) Condenser. (8) Palladous chloride absorbers (kept constantly at $52 \pm 2°$ C.) for hydrogen. (9) Condenser. (10) Water valve.

The furnace charge was increased from 2 grams to 10 grams of rhodochrosite for these experiments in order to increase the possibility of recovering hydrogen, since all quantities would then be larger.

Method.—(1) A blank experiment with nitrogen for 24 hours. (2) An experiment with a 10-gram rhodochrosite charge. (3) A repetition of the above two experiments with regenerated or new absorbers. Gases were passed at the rate of about two bubbles per minute. Temperature: 250° C.

Results.—Both blank experiments failed to show any effect on the hydrogen absorbers. Both rhodochrosite experiments showed the presence of reducing gases in the exhaust. A metallic film of palladium appeared on the surface of the $PdCl_2$ during these experiments.

The above results are confirmation of the fact that a reducing gas reaches the palladous chloride absorbers. Some CO may have reached the $PdCl_2$, although it is believed that ample precautions were taken to absorb it in the train. It is well known that CO is a troublesome gas to be absorbed, therefore the results here shown must be taken with this reservation. The detection of hydrogen would of course, indicate that the steam used in these experiments breaks down to furnish oxygen. The rather elaborate apparatus used for this purpose by the writer was shown to be necessary when hydrogen could not be detected by collection of the gases over a short period of time in ordinary apparatus.

[11] Gruner, J. W.: *Op. cit.*, p. 711.

DISCUSSION OF EXPERIMENTAL RESULTS.

The great stability of natural rhodochrosite at room temperature in air is shown by exposing it to alternate wet and dry conditions for a long period of time. Two experiments were made. Two grams each of powdered rhodochrosite No. 1 were put in two watch glasses. Water from the house tap was used for wetting. The wetting was repeated every other day for twenty-four months. About half of the time the mineral was dry. No trace of oxidation developed in either sample during this period. Gorgeu [12] long ago made similar experiments with like results.

Table II shows that natural rhodochrosite No. 1 is readily decomposed and oxidized by the aid of steam in 24 hours at temperatures above 170° C. No other source of oxygen need be present except the steam and the CO_2 from decomposition of the

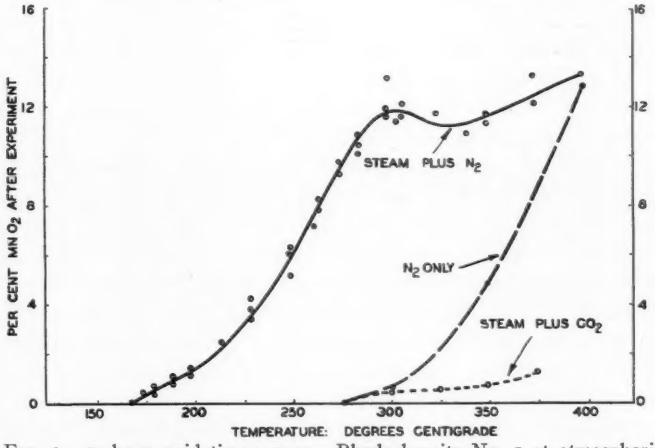

FIG. 2. 24-hour oxidation curves. Rhodochrosite No. 1 at atmospheric pressure.

rhodochrosite. The degree of this oxidation increases with the temperature up to about 300° C. At this temperature MnO_2 may not be stable and lower oxides are probably formed instead. This

[12] Gorgeu, A.: Bull. Soc. Chem., (2) vol. 49, p. 668, 1888.

point is emphasized in Fig. 2. Just what combination of the various possible oxides exists in any of the products of these experiments it is difficult to say. A very vigorous effervescence takes place whenever any of the altered samples are treated with hydrogen peroxide, indicating the presence of some MnO_2.

There is a significant color change in the samples of Table III at 250° C. In the early stages the material is altered to almost black powder. With increasing time there is a gradual change to brownish-black. There seems to be a tendency for the lower oxides to form at the expense of the higher ones as time increases. The streaks of the more common manganese oxides show a relationship which bears out this contention. These colors of the more common manganese oxides are: pyrolusite (MnO_2), iron black; manganite (Mn_2O_3, H_2O), dark brown; hausmannite (Mn_3O_4), chestnut brown; braunite (Mn_2O_3, $xSiO_2$), brownish black.

All rhodochrosite specimens of various degrees of purity oxidize readily in the presence of steam at 200° C., as shown in Table IV. Rhodochrosite oxidizes much more readily in air when steam is present (Tables V and VI).

Polished sections of oxidized material for examination in reflected light were extremely difficult to obtain. The ¼ inch material of Table IV was used for this, and the grains had to be carefully cemented with collodion before mounting in sealing wax for polishing. The sections show that rhodochrosite is oxidized to pyrolusite along cleavage cracks in the rhodochrosite, by the action of steam in the absence of air, at the temperatures stated in the tables, in 24 hours. The pyrolusite showed immediate and vigorous effervescence with a drop of hydrogen peroxide.

The specimens of manganous silicate No. 7 (fowlerite) showed no hydrothermal oxidation in 24 hours at temperatures of 400° C. or less. Specimens of silicate No. 6, containing manganese carbonate in small percentages, showed oxidation at 300° C. in 24 hours (Table VII).

High pressures retard the hydrothermal oxidation of rhodochrosite (Tables VIII and IX). Oxidation takes place slowly

TABLE III.

OXIDATION OF RHODOCHROSITE NO. 1 IN A CONTINUOUS FLOW OF STEAM AT ATMOSPHERIC PRESSURE.

Temperature: 150° C.				Temperature: 215° C.			
Exper. No.	Time in hours.	Per cent MnO_2 after expt.	Per cent of MnO converted to MnO_2.	Exper. No.	Time in hours.	Per cent MnO_2 after expt.	Per cent of MnO converted to MnO_2.
7	24	None	—	25	24	2.37	1.92
8	72	"	—	26	24	2.45	1.98
				61	72	4.57	3.68
9	144	"	—	62	72	4.71	3.79
10	240	" [a]	—	63	120	7.53	6.00
11	240	" [a]	—	64	120	7.68	6.12
Temperature: 175° C.				**Temperature: 250° C.**			
14	24	0.35	0.29	2	24	6.24	4.98
15	24	0.29	0.24	4	24	6.09	4.87
16	48	0.80	0.65	57	72	7.52	5.99
				58	72	7.38	5.89
13	72	1.07	0.82				
				1	120	8.39	6.66
12	120	1.62	1.32	56	120	8.25	6.55
17	120	1.54	1.26				
				59	240	13.14	10.27
				60	240	13.01	10.16

[a] Material becomes deep yellow in color.

TABLE IV.

OXIDATION OF RHODOCHROSITE FROM VARIOUS LOCALITIES IN A CONTINUOUS FLOW OF STEAM AT ATMOSPHERIC PRESSURE. TIME:—24 HOURS.

Rhodochrosite No.	2.	3.	4.	5.	2.	3.	4.	5.
Temp. ° C.	Per cent MnO_2 after experiment.				Per cent of MnO converted to MnO_2.			
200	1.20	Trace	Trace	0.31	0.94	—	—	0.25
200	1.27	Trace	Trace	0.27	1.04	—	—	0.22
225	3.75	2.98	1.86	3.13	3.03	2.41	1.51	2.50
225	3.82			3.21	3.09			2.59
250	6.18	5.18	5.01	5.76	4.94	4.17	4.02	4.61
250	6.23				4.99			
275	10.37	8.10	8.16	9.13	8.16	6.45	6.50	7.24
300	10.44				8.24			

at high pressures when a little HCl is present. Color changes indicate that the oxidation might take place even without HCl if the experiments could be continued over a longer time. (Apparatus for such work would be so expensive as to make its construction impossible at present.) Oxidation in these experiments is probably retarded by the CO_2 remaining after removing air from the bomb.

TABLE V.

OXIDATION OF RHODOCHROSITE NO. 1 IN STEAM WITH AIR AT ATMOSPHERIC PRESSURE. TIME:—6 HOURS. TEMPERATURE:—200° C.

Exper. No.	127.	128.	129.	130.	131.	132.
Per cent MnO_2 after expt.....	13.50	14.17	12.95	14.52	5.15	5.32

In experiments 127 to 130 a weak air current was supplied by a blower. In experiments 131 and 132 air was passed by natural draft.

TABLE VI.

OXIDATION OF RHODOCHROSITE NO. 1 IN A CURRENT OF AIR AT 200° C., AT ATMOSPHERIC PRESSURE. NO STEAM USED.

Exper. No.	Time in hours.	Per cent MnO_2 after expt.	Remarks.
133	6	7.90	Air current supplied by blower
134	6	8.11	" " " " "
135	24	2.27	Air current by natural draft
136	24	3.01	" " " " "

TABLE VII.

OXIDATION OF MANGANOUS SILICATE NO. 6 IN A CONTINUOUS FLOW OF STEAM AT ATMOSPHERIC PRESSURE. TIME:—24 HOURS.

Exper.	Temp. ° C.	Per cent MnO_2 after experiment.
93.....	300	Trace
89.....	350	0.28
90.....	350	0.25
91.....	400	1.07
92.....	400	0.88

Fowlerite No. 7 was not oxidized in 24 hours in a continuous flow of steam at atmospheric pressure, at temperatures of 400° C. or lower.

Table X indicates that rhodochrosite remains stable at 250° C. for at least 24 hours when steam or other sources of oxygen are not present. It starts to decompose at about 275° C., and oxidation of the manganese takes place due to the dissociation of the CO_2 contained in the rhodochrosite. In an atmosphere of air-free CO_2, at atmospheric pressure, rhodochrosite remains stable for 24 hours even above 275° C. (Table XI). Even at 300° C. the oxidation is slight and occurs only in a thin skin of the mineral powder at the top of the charge. It appears that the carbonate underneath is surrounded by an envelope of protective gases which are not swept away. In an atmosphere of CO_2 and steam, rhodochrosite begins to oxidize at about 275° C. The effect of increased temperature is very small. Here again the oxidation takes place only in a thin skin at the top of the charge (Table XII).

The irregular behavior in experiments Nos. 36 to 53 in Table II (see also Fig. 2) between 300° and 400° C. is strongly suggestive of complex chemical reactions occurring within this temperature range. It seems likely CO, generated by the dissociation of CO_2, may at this stage become comparatively more effective as a reducing agent. Clevenger and Caron[13] found that natural pyrolusite is reduced by CO or H_2. With CO the reduction begins at 87° C. and with H_2 at 190° C. The presence of steam in the system may complicate matters in such a way that this effect is not marked until a temperature of about 300° C. is attained. Much depends also upon the speed, in the experiments or in nature, with which the reacting gases are removed.

The complex series of chemical reactions involved probably includes several of the following:

$$MnCo_3 \leftrightarrows MnO + CO_2,$$
$$2\ CO_2 \leftrightarrows 2\ CO + O_2,$$
$$3\ MnO + CO_2 \rightleftarrows Mn_3O_4 + CO,$$
$$2\ MnO + CO_2 \rightleftarrows Mn_2O_3 + CO,$$
$$2\ MnO + O_2 \rightleftarrows 2\ MnO_2,$$
$$MnCO_3 + H_2O \rightleftarrows MnO_2 + H_2 + CO_2.$$

[13] Clevenger, G. H., and Caron, M. H.: The Treatment of Manganese Silver Ores. U. S. Bureau of Mines, Bull. 226, p. 42, 1925.

TABLE VIII.

BOMB EXPERIMENTS. OXIDATION OF RHODOCHROSITE NO. 1 AT HIGH PRESSURES IN STEAM AND CO_2. TIME:—24 HOURS.

Exper. No.	Temp. ° C.	Pressure in atmospheres.	Remarks.
94	200	15.34	Color changes to pinkish brown
95	200	15.34	" " " " "
96	225	25.16	" " " " "
97	225	25.16	" " " " "
98	250	39.23	Color changes to yellowish brown
99	250	39.23	" " " " "
100	275	58.66	" " " " "
101	275	58.66	" " " " "
102	300	84.78	" " " " "
103	300	84.78	
104	325	119.01	" " " " "

(*a*) No MnO_2 detected in any of the residues.

(*b*) The weight losses gradually increased with rising temperature. These varied from about 10 per cent at 200° C. to 20 per cent at 325° C. The losses are due in part to the difficulty of fully recovering the residue and in part to loss of CO_2 by dissociation. Volatilization may also be important.

(*c*) About 0.25 gram of material was used in each experiment.

(*d*) The water used varied from 25 cc. at 200° C. to 20 cc. at 325° C. In all cases the residue was still wet at the completion of the experiment.

TABLE IX.

BOMB EXPERIMENTS. OXIDATION OF RHODOCHROSITE NO. 1 AT HIGH PRESSURE IN STEAM AND CO_2. ONE DROP OF DILUTE HCl ADDED TO CONTENTS OF BOMB. TIME:—24 HOURS.

Exper. No.	Temp. ° C.	Pressure in atmospheres.	Oxidation.	Remarks.
161	150	4.70	None	No color change
160	170	7.82	Trace	
105	200	15.34	"	
106	200	15.34	"	
107	225	25.16	"	
108	225	25.16	"	
109	250	39.23	"	a,b,c,d,e
110	250	39.23	"	
111	275	58.66	"	f
112	275	58.66	"	
113	300	84.78	"	g
114	300	84.78	"	

[a] No MnO_2 in residue from the bomb.

[b] Color changes are comparatively stronger than those of Table VIII.

[c] Weight losses are comparatively greater than those of Table VIII. Original amounts of water and of mineral are the same as in Table VIII.

[d] In each of the experiments at 170° C. and above, a small amount of MnO_2 was deposited in the valve just below the asbestos plug. This varied (by estimate) from about 1 mg. at 170° C. to about 3 mg. at 300° C.

[e] In each of the experiments at 250° C. or higher, a deposit of brownish-yellow iron oxide formed at the very top of the valve.

[f] Residues are darker than in experiments 109 and 110.

[g] Residues are darker than in experiments 111 and 112.

APPLICATION TO GEOLOGICAL FIELD DATA.

Based on experimental evidence, it is believed that at least some hydrothermal influence may be postulated in the genesis of the manganese oxide deposits of the world.

In the *Gold Coast Colony and Ashanti,* Bishopp and Hughes [14] have indicated a strong relationship between the manganese oxides and igneous intrusions. Igneous rocks of wide variety, some of them manganese-bearing, invade the sedimentary or metamorphic rocks everywhere in the vicinity of the commercial manganese deposits. The largest ore deposits are characterized by loci of concentration at phyllite-porphyry contacts. "The phyllite is enriched in zones of varying width, everywhere along such contacts. Where a slab of phyllite is sandwiched between two porphyry intrusions, enrichment proceeds from both contacts." The most intense concentrations occur at the intersections of faults with these contacts. The faulting relationship seems to be especially important in the smaller ore bodies on the Asikuma belt. "On the other hand, the huge ore bodies of the Insuta and Dagwin hills appear to be due to the enrichment of blocks of phyllite set among the branching arms of a great porphyry intrusion."

They also state:—"The usual experience when sinking in ore bodies at Asikuma, Dixcove, and places outside Insuta, was that the ore body tapered out towards the water table and merged into enriched phyllite of a grade that would not be classed as ore." To the writer, such an arrangement indicates strong depositional activity and oxidation at intrusive stages. Supergene enrichment by removal of valueless material gave rise to commercial ore. Also, in the Dixcove area, Bishopp and Hughes mention that "the possibility of concentration by hydrothermal processes cannot be ignored."

The manganese deposits of *West Central Sinai* also offer some interesting features which seem to attribute them, in part at least,

[14] Bishopp, D. W., and Hughes, W. J.: Trans. Inst. Min. and Met., vol. 39, pp. 142–191, 1930.

TABLE X.

OXIDATION OF RHODOCHROSITE NO. 1 IN A STREAM OF NITROGEN AT ATMOSPHERIC PRESSURE. NO STEAM. TIME:—24 HOURS.

Exper. No.	Temp. ° C.	Per cent MnO_2 after expt.	Per cent of MnO converted to MnO_2.
137	200	None	—
138	200	"	—
139	225	"	—
140	250	"	—
141	275	Trace	Tr.
142	300	0.57	0.47
142-A	300	0.63	0.51
158	350	5.09	4.09
159	400	12.87	10.05

TABLE XI.

OXIDATION OF RHODOCHROSITE NO. 1 IN A STREAM OF CO_2 AT ATMOSPHERIC PRESSURE. NO STEAM. TIME:—24 HOURS.

Exper. No.	Temp. ° C.	Per cent MnO_2 after expt.	Per cent of MnO converted to MnO_2.
143	200	None	—
144	200	"	—
145	225	"	—
146	250	"	—
147	250	"	—
148	275	"	—
149	300	0.31	0.25
150	300	0.38	0.31

This group shows a slightly increased darkening of the sample with temperature increases. Oxidation took place only in a thin skin of material at the top of the charge. See also Table XII.

TABLE XII.

OXIDATION OF RHODOCHROSITE NO. 1 IN STEAM AND CO_2 ATMOSPHERE AT ATMOSPHERIC PRESSURE. TIME:—24 HOURS.

Exper. No.	Temp. ° C.	Per cent MnO_2 after expt.	Per cent of MnO converted to MnO_2.	Exper. No.	Temp. ° C.	Per cent MnO_2 after expt.	Per cent of MnO converted to MnO_2.
115	200	None	—	117	325	0.59	0.48
				124	325	0.59	0.48
115-A	250	"	—				
				118	350	0.64	0.52
120	275	Trace	Tr.	123	350	0.62	0.51
121	275	"	"				
				119	375	1.25	1.02
116	300	0.42	0.34	122	375	1.32	1.08
125	300	0.45	0.37				

CO_2 stream was freed of oxygen by passing over phosphorus.

The oxidation took place mostly in a thin skin of material at the top of the charge. This is in contrast to the results of tables II, III, V, VI, and X, in which the rhodochrosite was altered throughout the charge.

to hydrothermal activity. Ball [15] points out that the ores occur at the base of the Carboniferous limestones. The manganese is derived from the manganiferous dolomites of the area. These give way to ochreous sandy clays and shales wherever ores occur. The ore bodies are irregular, with a strong tendency to tabular or lenticular forms. The ores are definitely related to faults, showing thicker and richer deposits as the faults are approached. Ball suggests that the source of the waters which dissolved the dolomites and deposited the ores was "below." He points out that where only a portion of the dolomite has disappeared it is always the lower beds that have vanished. Concentration by downward circulation would lead one to expect the attack of the upper beds first. Even though the manganiferous dolomites extend over large areas, the ore bodies are confined to areas with basaltic rocks of later age than these dolomites. This combination of facts, indicates the action of hot waters, if not of hydrothermal activity proper. The basalts may possibly represent a source of additional manganese-bearing solutions.

At *Postmasburg, South Africa,* Du Toit discusses evidence of hydrothermal activity [16] in the concentration of manganese oxide ores. He divides the genesis of the ores into two periods. The first period he regards as one of supergene activity. For the second he postulates epi- or mesothermal conditions. A temperature above normal is evidenced by the abundance of diaspore in the "nonreplaced" shales as well as in the ores. Rose-pink soda-rich margarite (ephesite) is present in places, and specularite veins are formed in the quartzite roof. The colloform nature of the ores negatives a very high temperature, he says, but he notes the formation of opal at temperatures between 100° and 200° C. He considers the deposits as being of hypogene origin, suggesting that heat would have aided the precipitation of manganese. In a general way the richest ores of manganese tend to occur near the bottom of the zone, particularly where dolomite forms the footwall.

[15] Ball, John: Geography and Geology of West Central Sinai. Cairo Government Press, 1916.

[16] Du Toit, A. L.: ECON. GEOL., vol. 28, pp. 95–122, 1933.

Du Toit also mentions the catalytic property possessed by MnO_2 of precipitating Mn from solution, and suggests its application here.[17] One gathers from Zapffe's explanation of this phenomenon, however, that a source of oxygen must be provided, such as he obtained by strong aeration. Since air is not available with deep-seated conditions other sources for the oxygen must be sought. The experiments already described in this paper offer a solution to this phase of the problem.

In *India* igneous activity has been widespread in the vicinity of the extensive manganese deposits. Fermor[18] believes the kodurite series (which contains many valuable deposits) to be manganese silicate rocks of igneous origin. He presents much evidence in support of this idea. He also shows that these rocks have been themselves again intruded. The depth to which the oxidized kodurite ores extend has not as yet been determined; it has long been known that they extend well below the present water level. Fermor concluded that 700 feet was a maximum to be expected under the influence of surface agencies. If deposits are found at much greater depth, the hydrothermal oxidation hypothesis may have to be called on as an explanation of ore genesis for these deposits. All rock in the deposits is much altered. Certain high-temperature minerals are present, which may lend strength to this hypothesis even now.

The other highly important group of deposits lies within the Dharwar series, *Central Provinces*. Fermor refers to the compact and crystalline nature of these ores as evidence of formation at depth or at least subjection to great pressures after the volume changes accompanying oxidation. The whole series has been intruded by a porphyritic biotite granite. The supposition is advanced that alteration of some of the silicates to ore took place "while the rocks were still at some distance from the surface."[19] They are termed deep or Archean secondary ores. Oxygen and water liberated during the metamorphism of adjacent manganese

[17] Zapffe, C.: Deposition of Manganese. ECON. GEOL., vol. 26, pp. 799–832, 1931.

[18] Fermor, L. L.: Geol. Survey of India, Memoirs, vol. 37, 1909.

[19] Fermor, L. L.: *Op. cit.*, p. 293.

ore deposits are called upon in addition to CO_2 from the same source, as ore-making agencies. Such an hypothesis cannot now be passed by without reference to the experiments recorded in the present paper.

The *Chiaturi* (*Tchiatouri*) manganese deposits in the Caucasus are of sedimentary type. Yet an interesting relation to igneous rocks has been developed in a recent paper by Markov.[20] The map which he used in estimating the enormous ore reserves shows areas of equal total thickness of manganese ore. The principal geological value of this to the present study lies in the fact that the ores are thus shown to become thicker and less interbedded with other sediments as they approach the main center of basaltic intrusion. It does not seem unreasonable, then, to assume that the manganese of this huge deposit had its source in the same center of thermal activity as the basalt. Hewett[21] noted that deposits of manganese oxide nodules on the sea bottom are most abundant on the slopes of volcanic islands.

On the *Mesabi Iron Range,* numerous veins of manganese oxides occur in the ore bodies. Localization of these with respect to quartz veins and dikes penetrating the ore bodies is frequently noted. Gruner[22] states:

> Large quartz veins have caused local structures in ore bodies. They may branch at higher levels. Besides quartz, they contain much biotite (probably stilpnomelane) in needles, chlorite, and a little apatite. Manganese oxides are commonly associated with the ore near quartz veins. One vein near Buhl contained crystallized native copper.

More recently, Gruner[23] collected some excellent large crystals of magnetite from certain ore conglomerates in the above-mentioned area.

In the *Montreal Mine, Gogebic Iron Range,* Dick and Eide-

[20] Markov, C.: The Tschiaturi Manganese Deposits. U. S. S. R. Geol. and Prosp. Service, Trans., vol. 27, pp. 1–41, 1931.

[21] Hewett, D. F.: Manganese in Sedimentary Rocks. W. H. Twenhofel's Treatise on Sedimentation, p. 411, 1926.

[22] Gruner, J. W.: Contributions to the Geology of the Mesabi Range. Minn. Geol. Surv., Bull. 19, p. 27, 1924.

[23] Gruner, J. W.: Magnetite Cementing Certain Ore Conglomerates of the Mesabi Range. ECON. GEOL., vol. 29, pp. 757–760, 1934.

miller [24] note the occurrence of manganese oxides at the greatest depths so far opened up, 2600 feet. Manganese is apparently in the form of pyrolusite, since the miners come up from work "looking like negroes." The manganese content is as high as 25 per cent. The hydrothermal criteria of the Gogebic Range have already been discussed.[25] Rhodochrosite is still present in the ores and may have been the original source of the oxide minerals.

In the *Iron River District, Michigan,* hausmannite and braunite are the most abundant manganese oxides.[26] They occur in appreciable amounts even at the greatest depths attained in mining. A few basic dikes intrude the ores. Basic intrusives are common elsewhere in the adjacent formations.

Numerous other interesting relations between manganese oxide deposits and thermal activity exist in various places. The scope of this paper permits only brief remarks upon some of these.

Hanson [27] mentions two manganese oxide deposits in Canada. One of these is in the *Magdalen Islands, Quebec.* The ores are near the contact of diabase and red sandstone. The rocks may have originally contained manganese carbonates which were subsequently altered to oxides by the hydrothermal activity accompanying intrusion of the diabase. Logan [28] advanced this idea long ago. Several small deposits of manganese oxides are found about thirty miles to the north of *Port Arthur, Ontario.* These are in the Sibley series, which is intruded by the diabase dikes of the district. One deposit is a vein of massive, finely crystalline braunite and psilomelane.

Manganese oxide deposits of unusual nature have been described by J. T. Pardee.[29] These are near *Lake Crescent and Humptuleps,* in the state of Washington. A special interest in these deposits centers around the mineral bementite, a hydrous manganous silicate. This mineral is rarely noted elsewhere.

[24] Dick, L. E., and Eidemiller, H. W. Written communication.

[25] Gruner, J. W. *Op. cit.*

[26] Scofield, L. M. Written communication.

[27] Hanson, G. Manganese Deposits of Canada. Canada Geol. Surv., Econ. Geol., Ser. 12, pp. 98 and 102, 1932.

[28] Logan, W. E.: Geology of Canada, p. 508. Geol. Surv. Canada, 1863.

[29] Pardee, J. T.: U. S. Geol. Survey, Bull. 795, pp. 1–24, 1927.

Hausmannite is also prominent. Pardee calls upon igneous action to explain the origin of these deposits. Basaltic lavas are closely associated with the ores. These or deeper igneous rocks are considered as sources of the hot waters required in the alteration.

CONCLUSIONS.

1. Experimental work shows that rhodochrosite may be altered by steam to mangano-manganic or to manganic oxide at temperatures as low as 170° C. The presence of pyrolusite in the alteration product is highly probable, as indicated by the H_2O_2 tests.

2. The degree of oxidation increases with the temperature up to about 300° C. Above 300° C., complex alteration products seem to form. These products are a combination of manganic and manganic-mangano oxides.

3. If CO_2 is added to the steam, the above-mentioned alterations are retarded to a marked degree.

4. High pressures have an adverse effect upon the hydrothermal oxidation of rhodochrosite. When HCl is present, however, the oxidation may take place, although at a much slower rate than when pressures are near atmospheric.

5. Rhodochrosite is somewhat more stable than siderite under hydrothermal conditions. The presence of much iron carbonate in isomorphous mixture with manganese carbonate makes for a lower temperature of hydrothermal oxidation of the mixture. This relationship also holds true in the thermal decomposition of these carbonates without steam. In ore deposits, this fact may account for some separation of the manganese and iron oxides.

6. Field studies show a great deal of evidence that hydrothermal oxidation of manganese minerals may have taken place. Large manganese oxide deposits occur in many places where igneous activity seems genetically connected with them. Some of the manganese oxide ores are found at such depths that they seem best explained by hydrothermal sources of oxidation.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
April 5, 1935.

THE BOLIVIAN TIN BELT.

FRIEDRICH AHLFELD.

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INTRODUCTION.

SINCE the excellent work of Myron Davy (1920), the Bolivian Tin Province has been the object of much detailed research. Its study throws light on many problems on the formation of igneous deposits, since here many types of deposits which elsewhere are destroyed have not succumbed to erosion. There is a continuous series of igneous rocks from granite to lava and tuffs, with mineral deposits of all depth zones from pegmatites to late hydrothermal deposits. A picture of this metallogenetic province has been given by the author [1] as a result of many years of personal investigation and a review of the older literature. However, many important papers regarding it have appeared recently, and it appears advisable to present a short summary of the present knowledge of the province. Many questions have not yet been solved; geological and topographical maps are lacking; and such maps are necessary to demonstrate important tectonic features.

[1] Neues Jahrb. f. Min., Beil. Bd. 65, Abt. A, 286–456, 1932. Contains bibliography and maps.

FOLDING OF THE ANDES AND THE ASSOCIATED MAGMATIC CYCLE.

The oldest of the later foldings, Steinmann's so-called Peruvian (Senon), cannot be traced definitely in this region because of the lack of fossiliferous Cretaceous sediments. It is certain, however, that even before this folding there occurred large intrusions of basic magma which are now concordant in the Cretaceous sandstones. Important ore deposits are not connected with them. The second important folding, Steinmann's so-called Incaical, is certainly early Tertiary, probably Eocaical. According to Steinmann, the major part of the young acid rocks of Peru were formed in connection with this folding, but none of proven early Tertiary [2] age are known in this part of Bolivia. The batholith of aplitic granite which I found in the eastern part of the Cordillera Real between Yani and the Yungas of la Paz is possibly of early Tertiary age. The composition of this granite (Analysis 1) is similar to that of the late Tertiary granodiorites; however, it is folded in Paleozoic rocks and is now greisen. There is no doubt that it is older than the neighboring granodiorites of the Cordillera Real, but its exact age cannot be given. Although these granites lack tin, they are genetically connected with the hypothermal gold-quartz veins near Yani and elsewhere. Also, the alluvial gold of Tipuani and the Yungas may have originated from such quartz veins. This is a metallogenetic epoch characterized by gold and must perhaps be separated from the late Tertiary period.

The last distinct folding of the Andes is Steinmann's "Quetshuanic," probably late Miocene or Pliocene. It is disclosed in Bolivia in the neogene sandstones of the Altiplano, for instance in Corocoro. It was followed by eruptions of acid magma along north-south fractures and in anticlines of Paleozoic sediments. The ore deposits of the tin province are connected with these. After the conclusion of the ore formation the epeirogenic uplift of the Andes progressed. Toward the end of the Pliocene, volcanism in the middle and southern parts of the tin province pro-

[2] The age of the young magmatic rocks of Peru, especially of the granodiorites, does not seem to me to be fixed.

duced great volumes of acid tuffs (Analysis 9). The ore formation had now ceased. During the quaternary epoch the uplift of the Andes continued. Volcanism, however, was absent in the tin region, having migrated toward the inner edge, thence to the west, yielding basic effusives along a narrow north-south zone.

Within the late magmatic cycle, basic magma was produced first; then, during the phases of major folding and shortly after, acid magma, and later another basic phase.

THE TERTIARY PETROGRAPHIC PROVINCE.

The region of tin and related metals is a zone 600 Km. long situated in the Andes east of the Altiplano. Its greatest breadth lies in the latitude of Oruro, just where the Andes turn from northwest-southeast to north-south. The immense accumulation and intensity of mineralization at this point may be due to a particularly strong and deep fracturing that occurred here. Along such fractures magmatic residual solutions could rise in various parallel lines.

To the north and south, the zone of acid magma and ore deposits becomes narrower and less intense. Southward, the farthest tin and bismuth deposits lie near the Argentine frontier; to the north there are only rare deposits of tin and tungsten in Peruvian territory in the Cordillera of Apolobamba. The granodiorites near Cuzco, also late Tertiary, are free of tin. The tin gradually disappears to the north and south, whereas the eruptive rocks of the same age and composition continue.

The host rocks of the tin are Silurian and Devonian marine sediments, which were folded and later added to the Andine geosyncline and uplifted with the Andes block. They were included in the Paleozoic folds which also formed the western part of the Brazilian Shield. All the batholiths and most of the smaller intrusions are associated with anticlines of these Paleozoic sediments; only a few have penetrated the overlying Puca sandstone.

In the latitude of Arica, Bolivia is cut by lateral fractures and divided into separate blocks, of which those on the north were lifted higher and were therefore more affected by igneous activ-

ity. Due to differences in erosion, the present surface ranges from a few hundred meters in the south, to some 1,000 meters in the north, below the surface at the time of ore formation. Thus, batholiths are exposed in the north but in the south only their contact zones have been found, and dikes and necks predominate. The close connection of these types of rocks is evidenced by chemical and petrographic investigations. Formerly there was doubt as to their differences in age, but research has proved that there were not two different periods of ore formation —it was a continuous process (Davy, Singewald).

The age of the Potosi flora that occurs in tuffs metamorphosed by quartz-porphyry shows that this intrusion and the following mineralization are of Pliocene age, and this establishes the age of all the magmatic rocks of the tin province as Pliocene or late Miocene. The granitic rocks (a continuation of the partially Pliocene batholiths of the Cordilleras de Abancay-Apolobamba in southern Peru) which form the nucleus of the Cordilleras Real, Quimsa Cruz, and Vera Cruz show by their partial porphyritic texture and the regular occurrence of quartz-porphyry dikes that they consolidated at moderate depth. Exact calculation of this depth is impossible; it may be about 2,000 to 3,000 meters.

The small necks of middle and southern Bolivia are also to be considered intrusives, although they are commonly connected with lavas and tuffs. Proofs of this are the commonly microgranitic texture of the rocks (Oruro) and the contact metamorphism of the sediments. The shape of these necks has been called by Kozlowski and Jaskolski ethmolithic. Their horizontal diameter, extended on the surface, decreases in depth in the form of a funnel, changing into pipes (Cerro de Potosi, Fig. 1) or dikes at depth. Their depth must be regarded as very slight, about 200 to 500 meters. The extension of tuff breccias at their base (Colquechaca, Potosi) shows that originally the intrusions must have occurred as explosions, later followed by liquid magma (Jaskolski).

The arrangement of the necks shows connections with the fractures that parallel the axes of the Andes, as along the line

TABLE I.

ANALYSIS.

No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O+	H_2O-	P_2O_5	S	Cr_2O_3	Cl	BaO	SrO	ZrO_2	CO	B_2O_3	F_2	SO_3	Sum-mary
										A. Granitic rocks.														
1	72.73	0.12	14.96	0.40	0.98	0.02	0.02	1.02	3.06	5.22	0.78	0.12	0.12	0.00	....	0.03	0.02	.....	0.01	....	....	....	*	100.00
2	65.51	0.48	16.15	1.06	3.29	.....	1.92	2.54	2.22	5.42	1.22	0.10	0.40	.....	.....	.....	.not	dete	rmin	ed..	....	....	....	100.31
3	70.98	0.19	12.69	2.99	1.45	.....	1.04	2.56	3.03	4.59	0.57	0.13	....	.....	.....	. not	det	ermi	ned.	....	....	....	....	100.22
4	63.85	0.55	16.58	1.11	2.84	0.03	2.35	2.32	3.05	4.79	1.58	0.09	0.46	0.17	0.01	0.10	0.20	0.05	0.03	....	....	....	....	100.14
										B. Quartz porphyritic rocks.														
5	63.99	0.44	15.65	0.88	2.31	0.04	1.47	2.37	3.43	5.52	1.93	0.15	0.33	0.00	0.01	0.10	0.08	.....	0.03	1.26	....	....	....	99.98
6	67.20	0.67	14.40	0.39	3.82	.....	1.55	2.46	3.72	4.80	0.34	0.67	0.45	0.03	....	not d	eter	mine	d...	....	....	....	....	100.47
										C. Effusive rocks.														
7	69.90	0.75	12.03	3.78	1.26	0.15	1.10	2.64	3.72	4.62	0.27	0.52	0.21	0.08	....	.....	...n	ot de	term	ined	....	....	....	100.95
8	66.05	0.95	13.55	2.74	1.63	0.17	1.50	2.96	3.17	4.73	2.11	0.53	0.33	.....	.....	.....	.not	dete	rmin	ed..	....	....	....	100.44
9	73.02	1.29	14.20	0.28	1.11	0.07	0.42	0.87	3.18	3.33	1.21	0.72	0.18	....	....	.....	.not	dete	rmin	ed..	....	....	....	99.88
										D. Altered.														
10	67.75	0.24	18.45	0.95	2.04	.....	1.39	0.84	2.46	5.67	0.32					. not	det	ermi	ned.	....	....	....	....	100.11
11	60.19	1.98	13.15	2.17	11.86	traces	0.43	0.54	2.93	2.21	4.51	0.85	0.10	.....	....	.....	.not	dete	rmin	ed..	....	....	....	100.92
12	73.47	0.86	10.67	4.61	0.94	.....	0.41	0.42	2.49	4.70	0.70	0.96	0.15	0.41	.....	.....	...n	ot de	term	ined	....	....	....	100.79
13	95.62	0.54	0.72	0.37	1.00	.....	0.17	0.18	0.29	0.49	0.54	0.27	0.07	.....	....	.....	.not	dete	rmin	ed..	....	....	....	100.26
14	64.44	0.81	13.73	4.74	0.91	0.18	0.39	0.56	3.28	8.57	0.91	0.78	0.25	.....	....	.....	.not	dete	rmin	ed..	....	....	....	99.55
15	67.01	1.16	12.50	5.19	1.65	traces	1.30	1.11	1.83	5.51	1.59	0.51	0.38	0.59	...n	ot de	term	ined.	....	0.00	0.31	0.06		100.68
16	70.26	1.03	12.73	3.46	3.70	.....	0.80	0.49	1.87	2.14	0.23	0.53	0.32	0.92	....	. not	det	ermi	ned.	....	1.90	0.30	0.18	100.92
17	63.82	not det.	16.03	....	8.79	not det.	2.49	0.37	....	3.74	4.77	not det.	0.36	.....	....	.....	.not	dete	rmin	ed..	....	....	....	100.37
18	67.61	not det.	17.30	....	5.60	not det.	1.35	0.38	....	4.82	3.66	not det.	....	.....	.....	. not	det	ermi	ned.	....	....	....	....	100.72

Notes on opposite page. * Traces.

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Tasna-Chorolque-Choroma. The necks and batholiths, however, like the large batholiths in the north, lie in the anticlinal axes of the Paleozoic rocks that strike northwest.

All these igneous rocks chemically and mineralogically belong to a well defined petrographical province. Basic rocks are absent.

Table I shows the analyses available to the author. The older Yani granite (No. 1) is exceptional. All other hypabyssal, near-surface, and effusive rocks show a rather high Ca content and predominance of K. They belong to the family of Ca-alkali rocks. They can be called biotite-quartz-monzonite, with their

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EXPLANATION OF TABLE I.

1. Older Granite, Yani (Cordillera Real). Anal. Bendig (Ahlfeld: Neues Jahrb. Min. Beil. Bd. 65, Abt. A, 1932, p. 304).
2. Quartz monzonite, Caracoles. Anal. Helen Vassar (Lindgren: ECON. GEOL., vol. 21, p. 139, 1926).
3. Granite, Illampu. Anal. Brendler (Ahlfeld: Neues Jahrb. Min. Beil. Bd. 65, Abt. A, 1932, p. 305).
4. Porphyritic quartz monzonite, Illimani. Anal. Bendig (Ahlfeld: Neues Jahrb. Min. Beil. Bd. 65, Abt. A, 1932, p. 305).
5. Quartz porphyry, Colquechaca. Anal. Bendig (Ahlfeld: Neues Jahrb. Min. Beil. Bd. 65, Abt. A, 1932, p. 316).
6. "Microgranodiorite," San Pedro, Oruro. Anal. Jaskolski (Kozlowski: Archive Min. VIII, Varsovie, 1932, p. 17).
7. Red effusive rock, San Pedro, Oruro. Anal. Jaskolski (Kozlowski: Archive de Min. VIII, Varsovie, 1932, p. 21).
8. Black effusive rock, San Pedro, Oruro. Anal. Jaskolski (Kozlowski: Archive de Min. VIII, Varsovie, 1932, p. 23).
9. Dacitic tuff, Huanuni. Anal. Kittl. (Analysis de rocas eruptivas de Bolivia. Rev. Min. de Bol., 1927).
10. Slowly sericitized quartz porphyry, Llallagua. Anal. Brendler (Ahlfeld: ECON. GEOL., vol. 26, p. 243, 1931).
11. Quartz diorite, Cerro de Potosi, near Socavon Pailaviri. Anal. Jaskolski (Archive Min. IX, Varsovie, 1933, p. 55).
12. Quartz porphyritic rock near Muniza vein, Cerro de Potosi. Anal. Jaskolski (Archive Min. IX, Varsovie, 1933, p. 59).
13. Silicate rock, summit of Cerro de Potosi. Anal. Jaskolski (Archive Min. IX, Varsovie, 1933, p. 57).
14. Altered "microgranodiorite," Cerro Santa Barbara, Oruro. Anal. Jaskolski (Koslowski: Archive Min. VIII, Varsovie, 1932, p. 80).
15. Sericitized and pyritized "microgranodiorite," San José, Oruro. Anal. Jaskolski (Kozlowski: Archive Min. VIII, Varsovie, 1932, p. 83).
16. Tourmalinized "microgranodiorite," near San Luis vein, Itos mine, Oruro. Anal. Jaskolski (Kozlowski: Archive Min. VIII, Varsovie, 1932, p. 86).
17. Altered quartz monzonite adjoining ore, Llamero tunnel, Caracoles. Anal. Helen Vassar (Lindgren: ECON. GEOL., vol. 21, p. 141, 1926).
18. Altered quartz monzonite adjoining ore, Carmen Rosa vein, Caracoles. Anal. Helen Vassar (Lindgren: ECON. GEOL., vol. 21, p. 141, 1926).

Notes on opposite page. * Traces.

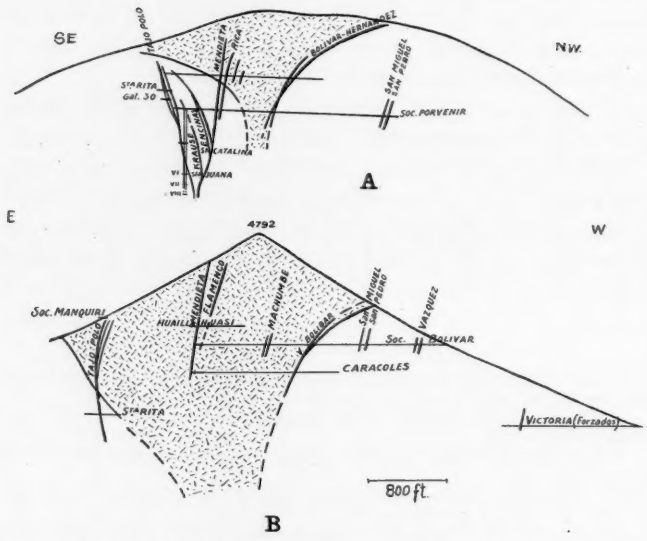

FIG. 1. Profile sketch of Cerro de Potosi. Scale approximately 1 : 10,000.

corresponding porphyritic and effusive rocks. The acidity varies widely, from 70.98 per cent. (No. 3) to 60.19 per cent. (No. 11). The quartz porphyry of Potosi (No. 12) is so rich in FeO that it must be called quartz diorite, whereas the rock of the Illampu should be called a normal granite. The sample for this analysis was taken from the deeply eroded central part of a batholith; the other samples are from the edge and upper zones. This points to the conclusion that the granitic batholiths have more basic peripheral zones. The same is also true of the large batholith of Andacaba, near Potosi. It has a decidedly basic peripheral zone consisting of a garnet- and corderite-bearing quartz andesite and a core of normal quartz monzonite. The quartz porphyritic rocks of the small necks are also commonly more basic (Cerro de Potosi). This explains the occurrence of tin ores in association with rather basic rocks—a combination which is local and not genetic. The ore solutions originated from deep acid rocks.

THE TERTIARY METALLOGENETIC PROVINCE.

Minerals and Their Paragenesis.

The Bolivian metallogenetic province characteristically contains those elements that predominate in other tin belts of the world; chiefly Sn, W, Mo, As, Bi, Cu, Zn, Pb, Sb; commonly Ag; rarely Au, Ni, Co, Hg; extremely common, B. Be is absent. Attention should be drawn to the similarity of the hypothermal zones with the Malayan tin belt, also the complete absence of uranium, which favors lower depths.

To give a reliable genetic system for the deposits, I made a special study of those minerals which form at comparatively low temperatures or vary in crystallization with variations of pressure and temperature. Only these will be described.

Tourmaline is extremely common. Macroscopically, it occurs in larger crystals and rosettes in the peripheral and upper zones of batholiths. More commonly, it accompanies tin ores as microscopically fine needles, inclined to be colorless, in quartz porphyries and as " tourmaline-hornfels " in contact zones. In near-surface rocks the needles may be so small that they are hard to identify (*e.g.* Potosi). Nothing is known about the lowest temperature at which it forms; although in general it is a high-temperature mineral, I observed it also in epithermal quartz veins at Montserrat.

Tin Ores.—The mode of occurrence of tin ores indicates the type of deposit. I have shown that cassiterite is a sensitive barometer, which, according to temperature, pressure, and kind of solutions, appears in various habits [3] (Table II). Cassiterite can form under very different temperatures, from above 400° C. down to below 100° C. The size of the crystals becomes smaller with falling temperature and pressure. The acicular type has a great interval of formation, from mesothermal to epithermal deposits. It is confined to near-surface deposits, and shows all transitions to the colloform type. Many so-called wood-tin occurrences show under the microscope radiating acicular texture.

[3] Ahlfeld, F.: Ueber Tracht und Genesis des Zinnsteins. Fortschr. Min. Kr. u. Pet. Bd. XVI, p. 303, 1931.

TABLE II.

Type	Chief forms	Twins	Phase of formation	Remarks
I	(111) (101)	Frequent	Pegmatitic	
II	(110) (100) (111) rarely (210) (320) stout	Almost always in twins	Pneumatolytic and hypothermal	
III	Stout or slender prisms with pyramids	None	Mesothermal	
IV	(110) (111) acicular along c	None	Meso- to epithermal	Mostly in "volcanic" deposits
V	Colloform textures		Mostly epithermal	Mostly in "volcanic" deposits

Real wood-tin is mostly of low-temperature near-surface formation. It is in all cases hypogene.[4]

Stannite [5] is, in Bolivian deposits of the "normal" type, hardly more common than in other tin-bearing districts of the world. Paragenetically, it follows cassiterite when copper is present, mostly perhaps as a reaction mineral between cassiterite and sulphide ores (sphalerite, chalcopyrite). It is much more common in the near-surface deposits of the Potosi type. The form and size of the ovoids due to unmixing, or the absence of them, indicate the conditions of formation. Only stannites of high-temperature formation contain such ovoids; in those of low temperature the chalcopyrite ovoids, otherwise prevalent, are absent. In their chemistry they correspond with the theoretical formula Cu_2SnFeS_4. In deposits of the "normal" type the formation of stannite lies in the hypothermal zone; in near-surface deposits, however, it includes the mesothermal and epithermal zones.

Teallite ($PbSnS_2$),[6] which is characteristic of Bolivia in the same way as the following sulphostannates, occurs only in epithermal deposits. The same is true of the slightly younger franckeite and cylindrite. With the formation of these minerals,

[4] By oxidation of stannite, masses of cassiterite are formed, mostly straw-yellow, brittle, and markedly inhomogeneous.

[5] Ahlfeld, F.: Ueber Zinnkies. Neues Jahrb. Min. Beil. Bd. 68, Abt. A, 1934.

[6] Ahlfeld, F.: Beitrag zur Kenntnis des Sulfostannate Boliviens, Teil I. Neues Jahrb. Min., Beil. Bd. 66, Abt. A, 1933.

the deposition of tin from the solutions ended. In places, needle-tin is found as the youngest mineral. A very small residue of tin remains in the solutions and enters into the minerals of the argyrodite-canfieldite group, which belongs among the youngest silver ores. Moritz [7] showed that germanium in the solutions is enriched only at very low temperatures. Stannite and teallite are free of germanium. In franckeite, Ge is more prevalent (up to 10.5 per cent.); in argyrodite-canfieldite it reaches 6 per cent.

Tungsten.[8]—The geochemistry of tungsten is of great interest. Only with high-temperature formation in the pegmatitic and hypothermal phase is it noticed that all members of the wolframite series (except those rich in Mn) are found. With decreasing temperature of formation a gap in mixtures occurs, so that in mesothermal and epithermal deposits members rich in Fe or those rich in Mn are found. Hübnerite and ferberite are found, mostly with antimonite and barite, in epithermal apomagmatic deposits. Scheelite is confined to pegmatitic quartz veins and is not common in the pneumatolytic and hypothermal tin deposits. Unique is the finding of white, microcrystalline scheelite in the Condeauque near Oruro, where the mineral occurs in an epithermal deposit. In the "volcanic" deposits of lower temperature formation, wolframite is absent.

Bismuth.[9]—Bismuthinite and native bismuth are the chief minerals in the "normal" deposits. Native bismuth, however, formed at slightly lower temperatures than bismuthinite. They have a small interval of formation in the hypothermal phase with chalcopyrite. In the "volcanic" deposits they are rare; their place is taken by bi-sulphosalts of various composition.

Gold [10] is generally absent where there is tin. In hypothermal quartz veins at greater depth, free gold is found in places with wolframite or scheelite. Farther down it occurs sparingly in

[7] Moritz, H.: *Idem*, Teil II.

[8] Ahlfeld, F.: Ueber die Verteilung des Wolframs in der boliv. Metallprovinz. Chemie der Erde, VII, 121–129, 1932.

[9] Ahlfeld, F.: Ueber die Verbreitung des Wismuts in der Zinnprovinz Bol. Zeit. f. prakt. Geol., vol. 41, 146–150, 1933.

[10] Ahlfeld, F.: Vorkommen und Gewinnung des Goldes im andinen Bolivien. Metall u. Erz, vol. 28, 163–167, 1931.

quartz-stibnite veins and in some bismuthinite veins (Esmoraca; San Pedro de Buena Vista).

Zinc is persistent in all sorts of deposits, but is rare in pegmatites (Fabulosa) and pegmatitic quartz veins. The dark sphalerite found in tin deposits almost always contains stannite, either in oriented intergrowths or, in deposits formed at lower temperatures, as unmixed products. The more transparent sphalerites in mesothermal to epithermal lead-zinc and silver veins are, on the other hand, free of tin. In the "volcanic" cycle in deposits of the Potosi type, sphalerite is less commonly present. It is common only in deposits formed at lower temperatures (Typ Poopó) where it was deposited first as the unstable wurtzite which predominates in some deposits (Monserrat; Carguaicollo). Sphalerite is commonly pseudomorphous after wurtzite.

Alteration of Rocks.

The mode of alteration of these rocks yields information as to the chemistry and temperature of ore solutions. Lindgren[11] found that in the altered quartz monzonites adjoining the tin veins of Caracoles large masses of iron silicates (chlorites) were formed.[12] Chloritization is, next to the tourmalinization in the granitic rocks previously mentioned, the predominant alteration. In the quartz porphyritic rocks various processes of alteration are telescoped one over the other. The rocks of Oruro, Potosi, and Chocaya have been examined microscopically and chemically by Kozlowski[13] and Jaskolski.[14] The latter distinguishes two phases of alteration of the dioritic rock of the Cerro Rico, Potosi; one, comprising the entire rock, consists of an auto-metamorphosis (propylitization) without the assistance of H_2S; a second more

[11] Lindgren, W.: Replacement in the Tin-bearing Veins of Caracoles, Bolivia. ECON. GEOL., vol. 21, pp. 135–144, 1926.

[12] *Idem:* Analyses 16 and 17, p. 141.

[13] Kozlowski, R., and Jaskolski, S.: Les gisements argento-stannifères d'Oruro en Bolivie. Arch. de Min., vol. VIII, Warsaw, 1932.

[14] Jaskolski, S.: Les gisements argento-stannifères de Potosi en Bolivie. Arch. de Min., vol. IX, Warsaw, 1933. Les gisements argento-stannifères de Chocaya en Bolivie. Arch. de Min., vol. XI, Warsaw, 1935.

local alteration, confined to the neighborhood of the veins and connected with ore formation, consists of silicification, sericitization, and pyritization (Analyses 11–13, Table I). According to Kozlowski, in the lower strata at Oruro tourmalinization predominates, with very little fluoritization. All depths show propylitization and sericitization, whereas silicification (Cerro de Potosi), the youngest process, is limited to the uppermost zones (Analyses 14–16, Table I). Slight sericitization was noticed in the quartz porphyry at Llallagua (Analysis 10, Table I). Alunitization, noticed in small amount at Oruro and Potosi, is a more recent process confined to the upper zones, and probably owes its origin (as does also the kaolinization) to the influence of surface waters reacting with the ascending H_2S-bearing solutions. In this case alunitization would correspond to the pyritization at greater depths.

Ore Deposits.

Classification.—Using the mineral content, the rock alteration, and the supposed depth of formation, I have classified the ore deposits of the Bolivian Tin Province as follows:

A. Deposits of the normal type
- I. Pegmatites and pneumatolytic deposits
  - *a.* Biotite and muscovite pegmatites and pegmatitic quartz veins containing Mo, Sn, W;
  - *b.* Pneumatolytic deposits containing tourmaline and cassiterite;
  - *c.* Pneumatolytic-hypothermal deposits, containing chiefly sulphide ores, with Sn, W, As, Bi, Cu.
- II. Hydrothermal deposits
  - *a.* Hypothermal gold-bearing quartz veins;
  - *b.* Hypothermal cassiterite, wolframite, and bismuthinite veins with sulphide ores;
  - *c.* Mesothermal and epithermal zinc-lead deposits;
  - *d.* Epithermal nickel-bearing veins;
  - *e.* Epithermal deposits with ferberite, hübnerite and scheelite;
  - *f.* Epithermal quartz-antimonite veins, sometimes with gold;
  - *g.* Epithermal cinnabar deposits.

B. Near-surface deposits, mostly in local connection with intrusions of quartz porphyritic rocks (deposits of the volcanic type)
  a. For the most part hypothermal deposits (Uncia type);
  b. Meso- to epithermal tin and tin-silver deposits (Potosi type);
  c. Epithermal zinc-tin deposits (Poopó type);
  d. Meso- to epithermal zinc-lead-silver deposits (Pulacayo type).
C. Alluvial deposits, containing Au, Sn, W, Bi.

Those deposits lying around the batholiths and showing mostly normal sequence from the perimagmatic to the apomagmatic deposits are here called deposits of the normal type. Separated from them are near-surface deposits, mostly in local connection with small intrusions of quartz-porphyritic rocks, here called deposits of volcanic type. They show a mineralization entirely different from that of the normal type. These types, however, cannot be strictly separated, since there are various intermediate deposits which are hard to determine definitely.

Deposits of Normal Type.—These deposits show in an admirable manner the zonal distribution around the batholiths. The pegmatites are found in the roof-zones; most of the hypothermal deposits lie within the inner zone of contact. Farther away in the outer contact-zone occur the mesothermal deposits, containing only a little tin, mostly Cu, Zn, Pb. The rest of the Zn-Pb veins and the antimonite veins lie in unaltered sediments.

Pegmatites are developed to a large extent only within the region of the Sorata batholith, Cordillera Real. In places they contain only molybdenite with biotite, elsewhere cassiterite and rarely, wolframite. On the southern end of this batholith, at the source of the Challana River, there is a large center of contact metamorphism with extensive contact zones (andalusite-hornfels and "knotenschiefer"). The granite is here developed in part as pegmatite and in part as greisen. In places it carries quantities of garnet. In it, and in the adjoining sediments, occur pegmatites in four generations. The latest carry cassiterite I, syngenetic with quartz; triplite, triphyline, lithium-muscovite, large quantities of stannite, also sphalerite, molybdenite and pyrrhotite. These veins are in part free from feldspar, hence pegmatitic quartz veins. The latter are widely distributed in the eastern

part of the Cordillera Real. Unlike the pegmatites, they carry cassiterite II, scheelite, and wolframite. Here also belong most of the tungsten deposits of northern Bolivia.

Strongly differing from these are the cassiterite deposits of pneumatolytic origin, which carry tourmaline, cassiterite II, quartz and a few sulphides, mostly pyrite. They are found on the western side of the Cordillera Real, *e.g.* near Caca Aca, in the Cordillera Tres Cruzes (Monte Blanco) and Vela Cruz (La Coya).

With lower temperature of formation, sulphides occur in great quantities, especially pyrrhotite, which, although one of the most common ores of the Bolivian deposits, has often been overlooked because through oxidation or other processes it was changed to pyrite-marcasite. In addition, occur chalcopyrite, bismuthinite, sphalerite, and a little stannite. The cassiterite is always of Type II. Tourmalinization of sediments is to be noticed in some places; in others it is lacking. Deposits of this type are widely distributed, chiefly on the western side of the Quimsa Cruz batholith (Araca; Chojnacota); in Colquiri; in the Colcha district; in Santa Teresa near Huari; on the Tasna.[15] In this locality the sulphide veins carry chalcopyrite, pyrrhotite, and bismuthinite; they are almost free of tin. On the Chicote Grande and on the Kami (Cochabamba district) they carry wolframite. Deposits poor in tin, wolfram, or bismuth merge into chalcopyrite veins.

Although these deposits show strong pneumatolysis, the following ores originated chiefly from hydrothermal solutions. The quartz veins carrying free gold are related to the quartz veins with scheelite and wolframite. They carry pyrrhotite, pyrite, arsenopyrite, occasionally wolframite, but no cassiterite. They are found sparingly near the batholiths in the northern part, *e.g.* in Chuquiaguillo near La Paz; Rosario mine, near Asiento (Araca); Choquetanga, Quimsa Cruz.

Some tin deposits occur in almost unaltered sediments and show

[15] Ahlfeld, F.: Der Wismutberg Tasna. Zeit. f. prakt. Geol., vol. 40, 119–125, 1932.

a paragenesis which points to lower temperatures of formation. The cassiterite is of Type III. Characteristic of this are some veins in Cerro Grande near Colcha, where cassiterite occurs with siderite.

Chalcopyrite veins merge into the mesothermal group. Chalcopyrite is common in some tin and bismuth deposits (Chojnacota; Tasna). The mesothermal chalcopyrite veins, mostly containing siderite, are free of tin.

Zinc-lead veins without tin, containing quartz, siderite, and rarely barite or fluorite, are common in all parts of the province. Those deposits nearer the batholith are richer in silver. Transitions to the stibnite veins are characterized by lead sulphoantimoniates.

Deposits with ferberite or hübnerite associated with quartz, stibnite, rarely with barite, are extensive and have in some cases been of economic importance (*e.g.* San Antonio near Colquiri). They are apomagmatic. Rarely ferberite is younger than stibnité (Lekkepalca, near Oruro).

On the Condeauque, northeast of Oruro, hot waters carrying wolfram have penetrated the Devonian sandstones. Their large content of Ca has led to the formation of white, microcrystalline scheelite in place of ferberite in the shales. The paragenesis scheelite-ankerite-barite points to the formation of these deposits under the same conditions as the neighboring ferberite deposits.

Quartz veins carrying stibnite with few accompanying minerals, occur over the whole district, mostly at the periphery. More than two hundred deposits have been found. These are mostly apomagmatic. In places they carry free gold.

Cinnabar deposits are rare. One deposit is known east of Cotagaita. The genetic position of the nickel veins in the Tapacari district, Cochabamba, is doubtful. They carry chloanthite, niccolite, and gersdorffite, with siderite and quartz. The fact that nickel ores (ullmannite) are in places associated with galena in Late-Tertiary veins seems to indicate that these nickel veins belong to the same metal province as the tin ores. They are always apomagmatic.

Deposits of Volcanic Type.—This group of polymetallic deposits is characteristic of Bolivia and is nowhere else developed to such an extent. The term volcanic applied to this group by some authors has led to misunderstanding, since these deposits are not always connected with near-surface intrusions, and such connection is not to be understood *genetically* but *areally,* since the veins in depth generally leave the eruptive rocks and pass into sediments, which means that the ore-carrying solutions do not originate in the small necks or pipes but come from deeper sources. The depth of the mineralization varies; some veins become impoverished a couple of hundred meters below the surface, others show normal mineralization at a depth of 600 to 800 meters, and it is not known to what depths the mineralization continues. In general the intensity of mineralization decreases, not always regularly, from above downward.

According to temperature of formation, it is possible to distinguish between some types that merge into one another. Decreasing temperature of formation produced such deposits as, Uncia, Chorolque, Potosi, Oruro, Chocaya, Monserrat, Actara. *Uncia* is an example of deposits in which hypothermal minerals are prevalent; *Potosi,* of those with few or no hypothermal minerals; *Poopó* of the following epithermal type; and *Pulacayo* is a variant free of tin or containing little tin with quantities of silver.

Uncia Type.—This type has its largest extension in the middle of the tin province in the latitude of Oruro. The veins occur in quartz-porphyry necks or in their immediate neighborhood (Uncia; Avicaya; Chorolque). Such deposits as Pozokoni (Huanuni), Morococala and Negro Pabellon, which occur in sediments without quartz-porphyry intrusions, show genetic similarity with deposits of the normal type (Class 1-*C*). In places, a trunk vein in depth branches towards the top (*e.g.* San Fermin vein, Llallagua). These deposits are characterized by strong tourmalinization of the eruptive rocks, cassiterite II, much pyrrhotite, rarely high-temperature minerals such as wolframite, bismuthinite, and a little stannite. Of greatest interest is the Uncia-

Llallagua deposit, the richest primary tin deposit in the world. The great amount of tin, bismuth, and wolfram here is to be explained as follows:[16] Along large fractures the overheated solutions rose close to the surface within the still hot quartz-porphyry body without appreciably losing their temperature. Here immediate precipitation occurred. Thus the larger part of the tin and related minerals was concentrated within a vertical zone of a couple of hundred meters. In Llallagua I could distinguish three primary depth zones, each telescoping the other. The lowest (600–900 meters below the surface) contains a large amount of tourmáline, cassiterite II; above is a middle zone that contains abundant tin in the form of cassiterite II, with wolframite, bismuthinite, native bismuth, a little stannite, and much pyrrhotite. Pyrite is rare. In the upper zone there are, in addition to the minerals of the middle zone, others of low-temperature formation such as stannite, cassiterite IV and V, wurtzite, Mn-wolframite, and franckeite. The telescoping is quite apparent.

The Chorolque deposit formed at lower temperatures. The stockwork-like deposit around the summit shows a paragenesis of minerals characteristic of the Potosi type—cassiterite IV and V, pyrite, and quartz, whereas at a depth of 800 meters cassiterite II is found in strongly tourmalinized quartz porphyry. Separated from them in the peripheral parts are chalcopyrite-bismuthinite veins and a quartz-wolframite vein.

Potosi Type.—This occurs chiefly in southern Bolivia but is found also in the middle (Oruro) and northern parts (Carabuco). In places the deposits follow north-south fractures, as in the Cordillera between Colquechaca and Potosi. They are mostly connected locally with quartz-porphyry necks or dikes, whose intrusion opened a path for the solutions, but some lie in Paleozoic anticlines or in Cretaceous sandstones remote from eruptive rocks (*e.g.* Vila Apacheta, east of Uncia). Those in quartz porphyries

[16] Ahlfeld, F.: The Tin Ores of Uncia-Llallagua, Bolivia. Econ. Geol., vol. 26, pp. 241–257, 1931. Turneaure, F. S.: The Tin deposits of Ilallagua, Bolivia. Econ. Geol., vol. 30, pp. 14–60, 170–190, 1935.

branch near the surface and pass downward into a few trunk veins.

The mineralization differs strongly from that of the Uncia type. Pyrrhotite (except in Oruro) is entirely absent, its place being taken by pyrite. Tourmalinization occurs (*e.g.* in Oruro), but is rare, and high-temperature minerals such as wolframite are mostly absent. Bismuthinite is rare; cassiterite occurs in types IV (needle-tin) or V (wood-tin); IV is prevalent in Oruro, V in Potosi and Chocaya. Quantities of stannite, lead-antimony sulphosalts (mostly with Ag), and in some deposits rich silver ores, occur. The variety of rare sulphosalts is large.

The large deposits of this type have considerable depth; on the Cerro Rico de Potosi ore occurs at a depth of 900 meters below the summit. The Utne and Bronce veins, almost extinct in the Caracoles level (4375 m.), contain good tin ores in the Santa Catalina level (4100 m.). The large trunk vein, Tajopolo, also contains good tin ore in the deepest levels, but very little silver ore. Here, the existence of strong mineralization can be inferred even down to 1200 meters below the probable surface at the time of ore formation.

Primary depth differences in mineralization are not so strongly developed as in Uncia, since the initial temperature was much lower and the decrease of temperature from below to above correspondingly less. It is noteworthy that in some veins the quantity of stannite increases with depth, whereas cassiterite decreases. In the Tajopolo vein, the content of stannite compared with the general tin content on the Caracoles level (4375 m.) was only about 5 to 10 per cent., and on the Santa Juana level (4000 m.) about 50 per cent. This fact must be connected with a change of concentration in the rising solutions, which in depth contained more copper, so that more stannite was bound to form below, and more cassiterite above. In the peripheral zone the veins contain much zinc, and in places barite, but tin is absent.

In Oruro the general conditions are similar to those in Potosi. In the Colorada vein, Chocaya la Vieja, however, the mineraliza-

tion shows no change from the surface down to the 500-meter level. It consists of cassiterite V with pyrite and quartz in rhythmical structure. Here Cu, Pb, Sb, Zn, and Ag ions were almost entirely absent, so that sulphosalts could not form.

The Potosi type can now be called mesothermal to epithermal. The solutions rose from great depths, and the influence of prewarmed spaces is negligible and cannot be proved. In the upper parts the solutions were in unstable equilibrium, and precipitation occurred immediately beneath the surface. The components originally, probably as ions, went through a sol-stage and were dissolved as mixed colloids which later on crystallized; hence the numerous colloform and rhythmic structures, chiefly of cassiterite, silica, pyrite, stannite, tetrahedrite, galenite, and many sulphosalts. I found also, in one vein near Llallagua, ferberite in concentrically-ringed and radiating aggregates. The rhythmic banding where the veins are brecciated, as in Chocaya, is remarkable.

The Vila Apacheta deposit, near Chayanta, well illustrates the colloform structure of ores which originates by rapid cooling of the solutions. Here normal cassiterite veins with pyrrhotite occur in Paleozoic schists. In one place solutions passed from the Paleozoic rocks into the overlying Cretaceous sandstones, and here only the entire mineralization shows colloform structure of great beauty—cassiterite in ball-shaped forms, their exterior covered with needles; pyrite, stannite, wurtzite, tetrahedrite. The reason for this is the sudden drop in temperature at the moment when the hot solutions penetrated the brittle sandstones. Analogous formations are found in the deposits near Colavi.

The Poopó Type.—In some deposits of the Potosi type, sulphostannates, mostly franckeite, occur abundantly as late minerals (Chocaya, Uncia), so it seems advisable to place these deposits in a group called the Poopó type after one of the chief occurrences. Veins of this type are widely distributed in southern and middle Bolivia, chiefly in the triangle Poopó-Antequera-Huanuni. They occur in quartz-porphyry rocks, but more commonly in unaltered Paleozoic rocks in the form of simple veins (Poopó, Monserrat, Porvenir mine near Huanuni). Where the adjoining rock is

quartz porphyry, it is sericitized and kaolinized. The depth of these tin ores is slight (up to 200–300 meters); pyrite and sphalerite predominate in deeper zones.

The mineralization differs widely from that of the Potosi type. Arsenopyrite, pyrite and stannite are among the oldest minerals. The chief ore is wurtzite (Monserrat, Carguaicollo); in deposits of somewhat higher temperature of formation, sphalerite is present (Antequera). Sulphostannates occur either as teallite ($PbSnS_2$) (Monserrat and Carguaicollo), or franckeite (Huanuni, Chocaya), rarely with cylindrite (Poopó) and lead-antimony sulphosalts of the jamesonite group. The latest mineral is hypogene needle-tin (type IV) (Monserrat). All these veins are remarkably banded. In Carguaicollo a teallite vein passes horizontally into a galenite vein. These veins are epithermal, and later than those of the Potosi type. Most of the minerals, such as franckeite, cylindrite, and a part of the complex sulpho-salts of the jamesonite group, are formed as mixed colloids.

Pulacayo Type.—These deposits are poor in tin or free from it. They lie chiefly in the southern part of Bolivia, in North and South Chichas and in Lipez, but are also found in the northern part (*e.g.* near Viscachani and Patacamaya). They are always associated with quartz-porphyry necks, and their occurrence is analogous to that of the Potosi type. Tin-bearing and silver-bearing veins commonly adjoin one another in the same neck (Colquechaca). The mineralization shows much variation; some veins carry sphalerite, galena rich in silver, and such silver minerals as pyrargyrite, miargyrite, native silver (Gallofa vein, Colquechaca); others contain pyrite, sphalerite, and tetrahedrite (Pulacayo; San Vicente). The temperature and depth of formation vary and are not always low, as shown by the occurrence of pyrrhotite and dyscrasite on the Embudo vein, Colquechaca. Tin ores are either entirely absent, as in Pulacayo, or present in very small quantity in the form of stannite, or argyrodite-canfieldite, as on the Gallofa-Embudo vein, Colquechaca. Bismuth minerals are rare (Colquechaca; Colorada vein, Animas); tungsten minerals are absent.

In many of these deposits colloform structures are displayed. The galena commonly displays a ball-like surface and radiating texture; pyrite shows shrinkage fractures (Fig. 2). Particularly interesting are the stalactites of tetrahedrite in Pulacayo.[17] One of these (Fig. 3), is about 10 cm. long, with a channel in the middle and a wartlike surface. It consists chiefly of a porous

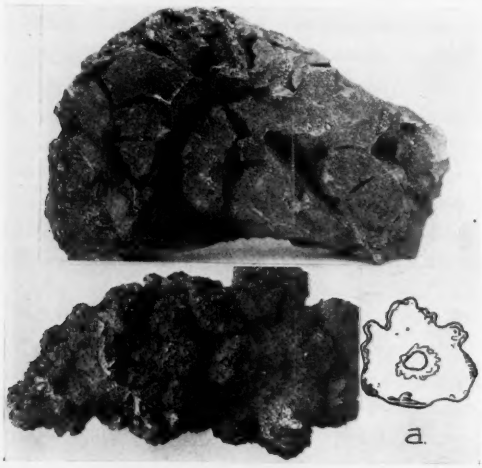

FIG. 2. Pyrite with shrinking fractures, Pulacayo. × 3/5.
FIG. 3. Tetrahedrite stalactites, Pulacayo. × 3/5. A, Sketch of cross section showing channel in center, tetrahedrite (white) pyrite layers (black), and peripheral galenite (striped).

mass of antimony-silver-tetrahedrite with two concentric strips of pyrite and a peripheral strip of galena, doubtless formed from concentrated colloids.

Most of the deposits described above lie in quartz-porphyry necks or in their adjoining sediments, but seldom in the effusive tuffs and flows. I saw one deposit in the effusives, that of Lomitos, near Chijmuni on the Oruro-LaPaz railway, where a stockwork-like deposit with mimetite as a hypogene mineral ad-

[17] One of these stalactites is in the Mineralogical Museum of Harvard University.

joining chalcedony and calcite occurs in a dacite flow.[18] Here mimetite was originally formed as a colloid. In the neighboring quartz porphyries of Laurani there are pyrite-enargite veins, unique in Bolivia. The genetic relation of these deposits with those of the tin province is not known. The enargite deposit possibly owes its origin to a late-Tertiary intrusion, but the mimetite deposit is of later age.

GENESIS OF THE DEPOSITS.

All deposits of the late-Tertiary metallogenetic province (with the exception of some deposits of uncertain origin and age) owe their origin to post-tectonic intrusions of acid magma and the differentiation of their rest-solutions. The differences in the mineral content of the deposits are to be explained by differences in pressure and temperature, which varied greatly with the distance of the source from the surface. The part of the deposits now visible originated in depths varying from a few hundred meters to some 1,000 meters.

Most of the deposits, or those of the "normal" sequence, as I have called them, form aureoles around the cupolas and sides of batholiths. In this respect, as well as in mineralization, they resemble other tin deposits of the world. An important difference lies in the fact that the percentage of sulphides, chiefly of pyrrhotite, is greater in Bolivia than in the geologically older tin provinces. This peculiarity can be explained by the fact that the intrusions occurred under a relatively small cover. The solutions coming from small intrusions and penetrating the sediments, cooled suddenly, and precipitation took place rapidly. A further reason for the prevalence of sulphide ores is the fact that the depth of erosion in the northern part of Bolivia was rather less than in the older tin provinces. Consequently, in Bolivia near-surface ores were preserved.

Apart from this difference, the mineral content coincides with that generally found in tin deposits, except that fluorine is scarce.

[18] Ahlfeld, F.: Ueber eine jungthermale Mimetesitlagerstätte in Bolivien. Neues Jahrb. f. Min., Beil. Bd. 66, 66, Abt. A, 41–46, 1932.

Pegmatites are scarce and are poor in metals. The pneumatolytic deposits are characterized by tourmaline, cassiterite II, and a few sulphides, and correspond to those of Cornwall and Saxony. The next zone contains the chief tin deposits and many sulphides, chiefly pyrrhotite. Tin was precipitated during a rather narrow temperature interval in the hypothermal phase; only small quantities occur in the form of stannite in the subsequent deposition with chalcopyrite and sphalerite.

The local separation of wolframite and cassiterite (their intervals of formation coincide almost entirely) is explained by the fact that cassiterite was formed by pneumatolytic processes in the highest parts of the covers above the batholith cupolas, whereas wolframite was formed mostly in pegmatitic quartz veins at greater depths. The same applies to the local separation of gold and tin. Gold favors hypothermal quartz veins of greater depth and is also found in small quantities in wolfram-bearing quartz veins. Bismuth was for the most part formed later than tin and wolfram, along with chalcopyrite in the hypothermal phase. This explains the almost quantitative separation of bismuth and tin in Tasna and elsewhere.

Farther removed from the magma, with falling temperature, the large group of lead-zinc veins with quartz, siderite or barite, rarely fluorite, were formed. Silver occurs chiefly in galena. Nothing definite can as yet be said about the genetic position of the nickel deposits. They are apomagmatic.

The vertical and lateral sequence of the many vein types mentioned above has not as yet been definitely determined. Evidently there are transitions from pegmatites through pegmatitic quartz veins with cassiterite, and wolframite; to quartz veins with wolframite and gold; and finally to local tungsten-bearing quartz veins with stibnite. In all these vein types, phases rich in gases play a part; the veins formed by processes rich in gases form a separate cycle. Hence, transitions from the pegmatites to the tin-bearing pneumatolytic veins are not observed. Possibly the gas phases separated directly from the magma. There are transitions from the pneumatolytic deposits to sulphide veins with cassiterite and pyrrhotite, through local chalcopyrite-bismuthinite veins on

to the zinc-lead veins and stibnite veins free from tungsten. Both lines of vein formation close with the stibnite veins.

The "volcanic" deposits, as I have called them, contain other mineral associations than the normal type. Gold and tungsten are mostly absent; bismuth is negligible, but silver is predominant. The fact that most of these deposits occur with quartz-porphyry intrusions is of areal rather than genetic significance. The intrusions were merely channels for the solutions to follow. As to how far the influence of the spaces pre-heated by intrusions played a part, it is hard to say; but it is certain that it did play a part in some of the deposits of the Uncia type. The paragenesis of the deposits of this group is almost the same as that of the hypothermal veins of the normal sequence; but they originated at lower depths and therefore telescoping is strongly developed. This group contains the largest tin producers.

With falling temperature, the character of mineralization was changed completely. Pneumatolytic processes no longer played a part. The influence of pre-heated spaces was negligible or absent. The temperature of ore formation may have varied between 300° and 150° C.[19] Influence of pressure was negligible; telescoping was much less developed. The minerals pyrite, cassiterite, sulphosalts of silver, antimony and lead commonly show colloform or rhythmic structure.

How then is the origin of such unique deposits as those of the Potosi type to be explained? We know from other tin regions, such as Cornwall, that tin was almost entirely precipitated in the pneumatolytic and hypothermal phases in the form of cassiterite. The tin ores are here almost localized in the immediate neighborhood of the granites. In the Potosi type the source was at great depth, probably several kilometers, as the mineralization scarcely changes with depth, and contact-zones in sediments have not been noticed. I wish to offer the following explanation for the genesis of these deposits:—Through deep fractures formed after the intrusion of batholiths and of near-surface masses, the solutions accumulated under high pressure were suddenly ejected to near the surface, and there, under rapidly decreasing temperature and

[19] Lindgren, on the Potosi deposit.

pressure, instantly yielded their metallic content. Therefore, tin had no opportunity to precipitate completely from the solutions at high temperatures near the batholiths, but remained in part in solutions in labile equilibrium. The components that originally existed as ions in solution went through a phase of sols and precipitated as mixed colloids which later unmixed and crystallized. The common rhythmical banding, the colloform structure of many ores, the often-noted impossibility of stating certain successions, the common occurrence of unstable modifications (*e.g.* wurtzite) and uncommon sulphosalts, all point to such conditions during solidification.

Most probably such deposits are not uncommon, but are normal types of near-surface deposits in all tin regions of the world. In other regions they may have fallen victims to erosion together with the small near-surface intrusions and extrusions formed with them, so that there remained only the deeper zones of hydrothermal deposits. One fact goes to prove this supposition, namely, that in some places in Bolivia, most characteristically on the Tasna and in Colquiri, where small batholiths penetrated high into the sediments, transitions are to be noticed from normal deposits to those of the Potosi type. Also in other tin regions of the world there are found remnants of near-surface deposits analogous to those of Bolivia, as in the rhyolith flows of Mexico; in the Akenobe District, Japan; in Freiberg, Saxony; and other places.

The genesis of deposits of the Poopó type remains unexplained. It is possible that the sulphostannates are reaction minerals formed by alkaline solutions in contact with cassiterite deposits in depth, whereby part of the tin may have dissolved and precipitated near the surface in the form of sulphosalts. Supporting this theory is the regional distribution of these deposits, always in areas that contain tin deposits, but often found distant from magmatic rocks and in the midst of unaltered sediments. Further investigation may solve these problems.

MINERALOGICAL INSTITUTE,
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GERMANY.
July 4, 1935.

THE BATTLE BRANCH GOLD MINE, AURARIA, GEORGIA.[1]

C. F. PARK, JR., AND R. A. WILSON.

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ABSTRACT.

The Battle Branch mine, in north-central Georgia, is well known locally for its pockets of exceptionally rich gold ore. During the period from May 24, 1934, to May 20, 1935, 781.97 ounces of bullion, of an average fineness of about 850, was shipped to the mint. The deposit is of the lode type; it consists of many quartz stringers and lenses grouped in three zones in a schistose phase of the Carolina gneiss. Three stages of mineralization are recognized. An early high-temperature stage produced coarsely crystalline silicates, such as garnet, kyanite, tourmaline, biotite, and muscovite, which were probably formed by a recrystallization of the minerals in the country rock. During the intermediate stage ankerite, quartz, and pyrrhotite were formed. The last stage was marked by chlorite, galena, and gold. Throughout the period of mineralization minor amounts of movement in and across the lode occurred. The distribution of the ore shoots is dependent to a large extent upon the distribution of the cross fractures. The ore shoots are pod-shaped bodies, which pinch and swell abruptly. The gold in the rich shoots is contemporaneous with galena and is clearly of hypogene origin.

[1] Published by permission of the Director, U. S. Geological Survey.

INTRODUCTION.

THE Battle Branch gold mine, an outstanding example of the high-temperature lode deposits of north Georgia, is on the west bank of the Etowah River, about one mile west of Auraria, Lumpkin County (Fig. 1). The property was studied in 1934 and 1935

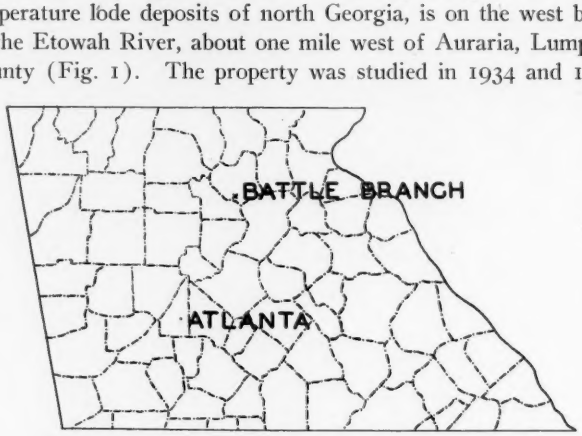

FIG. 1. Index map of northern Georgia, showing the location of the Battle Branch mine.

during an investigation of Georgia gold deposits by the United States Geological Survey under an allotment from the Public Works Administration. The mine contains unusually rich bodies of high-grade ore, and the opportunities for geologic study were exceptionally good. The conclusions reached in this paper will apply in general to many of the other mines and prospects in the region.

Gold is reported to have been found on the Battle Branch in 1831, and the property has been worked at irregular intervals since that time. Yeates [2] gives a fairly comprehensive historical sketch of the mine, and Jones,[3] Cain,[4] and Wilson [5] have mentioned it

[2] Yeates, W. S., McCallie, S. W., and King, F. P.: A Preliminary Report on a Part of the Gold Deposits of Georgia. Georgia Geol. Survey Bull. 4–A, pp. 475–478, 1896.

[3] Jones, S. P.: Second Report on a Part of the Gold Deposits of Georgia. Georgia Geol. Survey Bull. 19, p. 175, 1909.

[4] Cain, A.: History of Lumpkin County, Ga., pp. 97, 111–112, 1932.

[5] Wilson, R. A.: The Gold Deposits of Georgia. Georgia Dept. For. and Geol. Devel., Div. Geol., Inf. Circ. 4, pp. 4–5, 1934. (Notes by R. W. Smith.)

briefly. From 1917 the mine lay idle until January, 1934, when it was reopened by the Southern Mineral Development Co., and operations have been continuous since that time.

The mine workings accessible at present include the Gayden and Rogers shafts, which extend downward 195 feet on the plane of the lode. The dip of the lode and the Rogers shaft flattens from 35° in the upper part to about 30° between a depth of 85 feet and the bottom of the shaft. There are two levels, one at 85, and the other at 173 feet depth on the incline. The 85-foot level has about 280 feet of drifting; the 173-foot level contains about 285 feet and is at present being extended (Fig. 2). A tunnel south

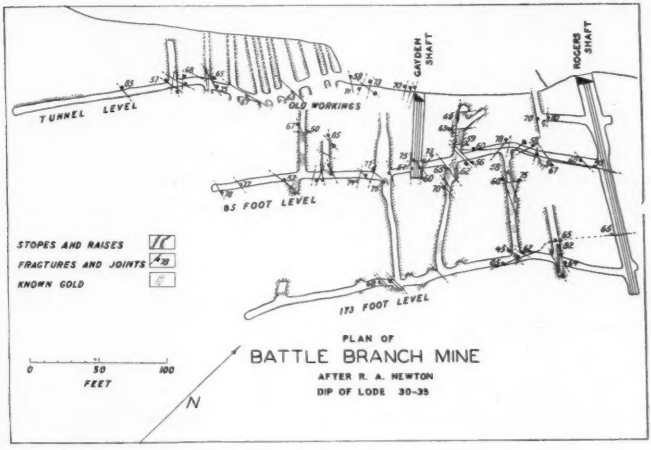

FIG. 2. Plan of the workings of the Battle Branch mine. (After R. A. Newton.)

of the shaft is about 253 feet long. In addition, many abandoned and partly filled inclines and drifts have been found and in places reopened.

No complete records of mine production are available. From May 24 to December 31, 1934, 327.53 ounces of gold and 20.82 ounces of silver, worth $10,232.52, were shipped. This ore was mostly removed by hand and pounded up in a mortar. A small

mill was installed in August, 1934, and has been worked since then. During 1935, until May 20, 454.44 ounces of bullion was produced.

C. G. Dickinson, W. T. Holland, W. C. Hansard, and R. A. Martin have acted as field assistants for part of the work, and R. W. Smith, State geologist of Georgia, has encouraged the study in many ways. The writers are especially grateful to R. A. Newton, the mine manager, for his cordial coöperation. In addition to his many courtesies in the field, Mr. Newton has generously contributed specimens of rich gold ore for microscopic and laboratory study. The authors also appreciate the critical reading of the manuscript by their colleagues on the Geological Survey.

GENERAL GEOLOGY.

A series of schists and gneisses, belonging to the Carolina gneiss, are intruded by dioritic and more basic sills and dikes of the Roan gneiss, and underlie the region adjacent to the Battle Branch mine.[6] The Carolina gneiss has been intricately folded and crumpled. Faulting is difficult to recognize, but it is likely that the mineralized zones, of which the Battle Branch lode is one, represent zones of considerable movement approximately parallel to the schistosity, N. 30°–45° E.

There are no natural outcrops near the mine except in the valley of the Etowah River. The surface exposures commonly consist of light-red or yellowish clay soil, which contains minute flakes of brownish, partly decomposed mica and small garnet disks. At a depth of a few feet there is a layer of decomposed rock or saprolite in which the texture is largely preserved; it consists mainly of clay together with such more resistant minerals as garnet and staurolite. At a depth of about 80 feet in the mine the saprolite changes rather abruptly into the unaltered Carolina gneiss.

The fresh country rock at the mine is a schistose phase of the Carolina gneiss, which strikes with the regional trend, N. 30°–

[6] Keith, Arthur: manuscript geologic map of Dahlonega special area.

45° E., ar
affected b
smooth th
red garnet
of the mo

FIG. 3.

45° E., and dips 20–43° SE. (Fig. 3). The schist, where least affected by the mineralization, is grayish brown and breaks in smooth thin plates which contain numerous flattened nodules of red garnet about one eighth of an inch in diameter. Biotite is one of the most conspicuous constituents, but it is quantitatively less

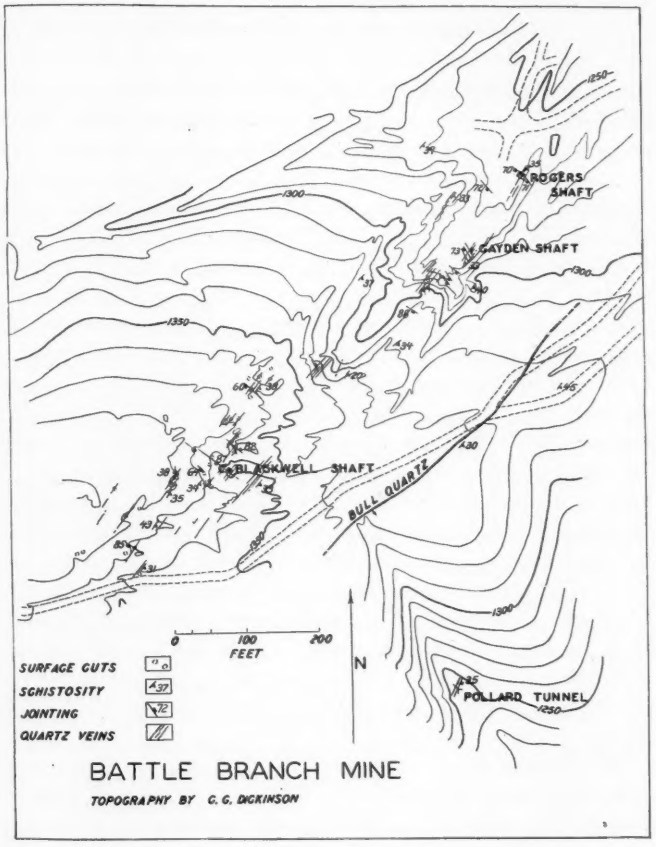

FIG. 3. Sketch map showing topography and geology in the vicinity of the Battle Branch mine.

than the fine quartz which it obscures. Muscovite is in places more common than biotite. A little pyrite is usually visible, and under the microscope kyanite, staurolite, and iron oxides are recognized. The schist is well exposed in the near-by valley of the Etowah River, where hard quartzitic bands alternate with the softer more micaceous layers.

Near the lode, the garnets become coarser and, adjoining the lode, form discoidal nodules as much as an inch in diameter; biotite and muscovite likewise are coarser, and quartz is more conspicuous. The rock is in general more quartzose; small quartz stringers are generally present, and the garnet in the nodules contains thin bands of quartz. Amphibole is present in nodules and narrow bands, generally less than half an inch thick, and in places as isolated crystals. The amphibole is green or greenish black; the darker variety is in long prismatic crystals (maximum length 2 inches), the lighter variety in thin layers of radiating acicular crystals. Pyrite and pyrrhotite are both widespread and conspicuous, the pyrite in well-formed cubes less than a quarter of an inch on a side, and the pyrrhotite in irregular thin bands and masses. Locally the schist contains lenses of dark-gray massive quartzite, which in places form the footwall of the lode. A narrow band of white, fine-grained, muscovitic marble is present in most of the underground workings. This band has a maximum thickness of about 4 inches but is generally 1 to 3 inches thick. In places two or more even narrower bands can be recognized. Some of this marble is so dense that it resembles chert spotted with small mica flakes. The marble band is approximately parallel to the foliation planes in the schist, but whether it represents an original recrystallized bed or later introduced material is unknown. Limestone is reported from other areas in the Carolina gneiss.[7]

The foliation planes in the gneiss form broad sweeping curves both on the strike and dip. The 85-foot and 173-foot levels in the mine have been driven approximately parallel to the schistosity (Fig. 2). Near the mine the schist is conspicuously jointed.

[7] Keith, Arthur: personal communication, 1934.

The joints are irregular on both the strike and the dip. The most persistent ones strike nearly east and dip north; grooving is well developed. Fractures that strike approximately parallel to the foliation of the schist and dip west are also found. These are open in places and serve as water channels. Some breccia and gouge are locally present. Both the water-bearing fractures and the joints, in some places, offset the quartz in the lode.

STRUCTURAL FEATURES OF THE LODE.

The Battle Branch lode is a zone of silicified and mineralized schist with numerous quartz lenses and stringers. The lode is not exposed across its entire width but is estimated to have a maximum width of about 30 feet. The lenses and stringers are mostly parallel to the schistosity but in places cut it. Eldridge,[8] who visited the property in 1879, says: "The gold occurs in . . . bands of quartz, which are not uniformly separated from each other. . . . They vary in width, at places being not more than 2 or 3 inches in thickness, while at others widening out and taking upon themselves lenticular forms, called pockets, which have an average dimension of 4 feet in length, though varying from 2 to 10 feet, a width of 6 to 8 feet, and a thickness of from 2 to 5 feet, at times there being a mere trace of the quartz from one pocket to the next."

The lode, as exposed underground, consists of three main streaks or "veins" and numerous smaller stringers and lenses in silicified schist. The three main streaks persist throughout the underground workings, but they pinch and swell abruptly, varying in width from a few inches to 2 feet or even more. In places two of the streaks merge and form quartz bodies 4 or 5 feet wide. The country rock between the streaks has a maximum width of 6 to 8 feet. A few narrow bands of marble are commonly seen in the schist near the quartz streaks.

The lode is crossed by many joints that strike in general between west and northwest and dip steeply either northeast or southwest. These joints are grouped around the crests of broad

[8] Eldridge, G. H.: field notes on file, U. S. Geological Survey, 1879.

rolls in the schistosity. The footwall of the lode, at the crest of the rolls, is quartzite, more massive than elsewhere. The groups of fractures appear to be tension cracks, formed by bending the brittle rock in the lode around massive quartzite lenses. A few water-bearing fractures strike approximately parallel to the lode but dip at moderate angles to the west. They generally contain a little gouge and breccia and offset the quartz a few inches to a few feet. This offset is of the reverse type, the hanging wall having moved up relative to the footwall.

The fact that the larger pockets of quartz and ore are concentrated along seams and breaks indicates that these breaks existed prior to the ore deposition. Some post-ore movement has occurred, however, as the quartz in places is slightly shattered and broken along both the northwestward-trending joints and the larger northeastward-striking fractures. Specimens of gold and galena that have been smeared along the fracture planes have been shown to the writers by Mr. Newton.

Ore Shoots.—The ore shoots are commonly localized by the intersection of joints or fractures with the main lode. Pre-existing joints and cracks cause notable irregularities in the outline of the shoots, in some places terminating the ore body abruptly and in others deflecting it into a new channel. The shoots are generally pod-shaped or tube-shaped, with the pods pinching and swelling down the dip or where the shoot is crossed by cracks. The shoots vary in size. Generally they are less than 5 or 6 feet wide by 2 feet thick, but exceptional bodies may be larger. The length of the shoots reaches a known maximum of about 100 feet, although in these longer bodies the ore occurs in a series of pockets connected by narrow gold-bearing streaks.

The ore in the shoots consists predominantly of quartz, galena, ankerite, and gold. Red almandite garnet commonly borders the ore, and some shoots are bounded by thin tube-shaped masses of garnet. Several shoots have been mined and one in particular was studied in considerable detail. It was followed from the 85-foot level upward along the intersections of several northwestward-trending joint planes with the lode. The richest pocket

found during the present operations occurred where this shoot intersected a fracture striking N. 40° E. and dipping 45°–60° NW. From this pocket 60 ounces of gold was obtained by hand in one day. The quartz at this point was stepped down about 1 foot to the south, along the intersecting fracture, but was otherwise not badly broken. The ore shoot described occurred in the middle one of the three main quartz bands; this was mined up into the hanging wall, and it was found that former miners had sunk on the upper band of quartz. The gold and galena in the quartz dipped at a slightly steeper angle than the quartz. Downward, the shoot pinched out about 15 feet below the 85-foot level, along a tight crack that strikes N. 80° E. and dips 58° N. Here the gold was concentrated near the footwall of the middle quartz layer; no exploration has yet been done on the lower quartz band. The ore in this shoot also occurred between two bands of red garnets; it crossed from side to side between them but did not cut them.

In general it appears that the ore is concentrated in shoots where joints or fractures cross the lode: the more numerous the fractures the better the ore. Fractures develop more readily on the crests of the rolls than on the flanks, and in the small amount of work so far done the indication is that the better ore occurs near the sharper bends in the formation.

The quartz in the lode between the ore shoots contains only small amounts of non-commercial ore.

MINERALOGY.

The mineralogy of the deposit is unusual in that such minerals as garnet, cummingtonite, tourmaline, kyanite, chlor-apatite, pyrrhotite, galena, and gold are intimately associated; twenty-two species have been identified. Miss J. J. Glass, W. T. Schaller, and J. J. Fahey have helped in the determination and checking of some of the minerals.

Gangue Minerals.—Quartz is the most abundant gangue mineral. It is commonly coarse, sugary, and white to light gray, and contains remnants and partly replaced fragments of the country

rock. A banded appearance is caused by the partly absorbed schist remnants and by thin elongate layers of muscovite and biotite. The quartz gangue generally contains numerous vacuoles and inclusions, in contrast to the large veins of barren, glassy white quartz which are also found on the property (Fig. 3). Bands of similar glassy quartz are locally present in the lode. Their relation to the ore deposits is undetermined.

Almandite garnet is common in the lode and in the adjoining wall rocks (Fig. 4). Three varieties are distinguished in the field—(1) a brownish discoidal form in the schist wall rock, in which the individual disks near the lode average half to three-

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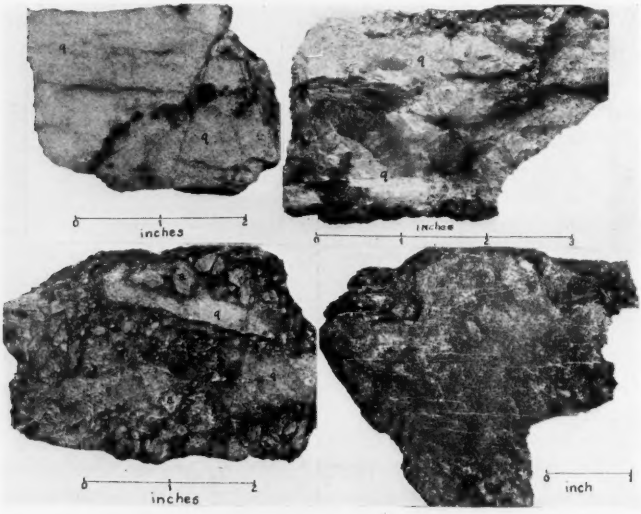

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6

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FIG. 4. Almandite garnet veinlet in banded quartz (*q*). The garnet is embayed and veined by quartz. The banding is caused by residual fragments of schist. Polished slab.

FIG. 5. Kyanite (*k*) in quartz (*q*), 170-foot depth, Rogers shaft.

FIG. 6. Polished slab of brecciated ankerite (*a*) cemented by quartz (*q*).

FIG. 7. Polished surface showing gold (white) in fractures in silicified Carolina gneiss.

quarters of an inch in diameter and become progressively smaller away from the lode; (2) a reddish, more or less euhedral form in the quartz and adjacent schist, in which the crystals are commonly three-quarters of an inch and may be as much as 1.5 inches in diameter; and (3) a black euhedral garnet in the schist adjacent to the quartz, in which the black crystals are generally less than three-quarters of an inch in diameter.

Chemical analyses show that the second and third varieties are almost identical, containing about 76 per cent. almandite, 14 per cent. grossularite, and 8 per cent. pyrope. The difference in color between the two is apparently due to abundant inclusions of magnetite in the black variety. The brownish discoidal variety shows a somewhat higher content of grossularite, pyrope, and spessartite and a lower content of almandite, although still over 70 per cent.

The red and black varieties are thought to be recrystallized forms of the more metamorphosed discoidal type. Locally the red and black varieties grade into each other. They occur throughout the lode, and in general are more common near the high-grade shoots than elsewhere. The crystals are commonly well formed but are slightly fractured and have parting planes developed.

Amphibole bands and nodules are abundant in the lode and in the wall rock, but are absent in the country rock. Two types are distinguished; a dark-green variety that occurs in coarse prismatic crystals as much as 2 inches long, and a somewhat lighter variety that is present in small radiating crystal groups. Both types have the optical properties of cummingtonite.

Kyanite is found in coarsely crystalline aggregates and sheafs in the quartz (Fig. 5). The longest crystal seen measured 3¼ inches. Coarse kyanite has not been seen in the country rock, although fine-grained kyanite is seen in thin sections of the wall-rock adjacent to the lode. A tubular mass of kyanite is reported to have occurred in the Rogers shaft between the 85- and 173-foot levels, lying in the lode just below a gold shoot. The mass ranged from a few inches to 2 feet in diameter. Kyanite has also been seen in other places in the ore.

Ankerite is common in the lode below the saprolite. It is milky white and generally occurs in sharply angular fragments in the quartz and coarse silicates. The carbonate has so far been a persistent constituent of the high-grade gold pockets and is considered to be an excellent indicator of ore (Fig. 6).

Calcite occurs in narrow bands of fine-grained sericite marble, which are present throughout the mine workings. The distribution of the ore is independent of the distribution of the marble.

Muscovite and biotite are both common constituents of the lode and country rock; in many specimens the two minerals occur together. Muscovite is more common in the lode than biotite, but in the wall rock the reverse is true. The micas in the lode are coarse; plates as large as three-quarters of an inch in diameter have been seen. Like the garnet, the micas become progressively finer-grained away from the lode. The muscovite is generally somewhat more coarsely crystalline than the biotite.

Much of the ore contains a fine-grained green mica. Enough of this mineral for an analysis was not obtained, but a qualitative test showed chromium in appreciable amounts.

Chlorite occurs locally in considerable quantities in both the lode and the country rock. It appears to form as an alteration product of other minerals, mainly biotite and cummingtonite. On the 173-foot level it is more noticeable than in the upper workings. It occurs abundantly with ankerite and gold. Carbonate is partly replaced by chlorite rims (Fig. 8).

Chlor-apatite is a rare constituent, but one smooth and corroded grain 0.6 by 0.4 by 0.2 inch was obtained. The grain was found in a specimen of high-grade ore associated with quartz, ankerite, galena, and gold.

Tourmaline in small black needles has been found in specimens on the mill dump from the 85-foot level.

Partly sericitized plagioclase feldspar occurs in material adjacent to the quartz bands. This feldspar appears to be residual in the schist; the mineral has been found only in small quantities. Its composition is indefinite, but is probably near sodic andesine.

A little staurolite occurs in the ore and is a common though not

abundant constituent of the adjacent schist. The staurolite in the ore may be a residual mineral, left after replacement of the original schist, although staurolite grains 3/8 inch long have been seen in the ore; the grains in the country rock are smaller.

Ore Minerals.—Gold is the only mineral sought at present, although galena forms a by-product of possible economic value. Gold and galena are the latest primary minerals and occur in fractures and irregular patches through the other minerals. The

FIG. 8. Sketch showing ankerite replaced by chlorite rim. *an*, ankerite; *cl*, chlorite; *gn*, galena; *Au*, gold; *q*, quartz.

gold is either angular or leaf-like; it coats garnet and has been seen in small flakes through the garnet and in thin layers between cleavage plates of mica. In some places the gold leaves the coarse minerals with which it is ordinarily associated and fills cracks in the silicified schist (Fig. 7).

The gold, is coarser than that from many other southern Appalachian deposits, and is generally visible. During recent operations the heaviest piece of gold obtained weighed 0.25 ounce; several weighing about 0.15 ounce were found. A nugget weighing about 0.7 ounce is reported to have been obtained from the old Weaver shaft by previous operators.[9] The estimated fineness of the gold is about 850 parts per thousand, but ranges from 750 to

[9] Summerour, D. A.: personal communication, 1935.

over 900. Specimens from the upper workings gave a fineness of 908.9, and from the 173-foot level, 742.8,[10] but most gold from the lower level is finer than this determination indicates. The fineness varies considerably, but in general the gold near the surface is finer than that obtained in depth. Bright-red gold is found near the face of the upper tunnel, below the old Glory shaft. This gold owes its color to a very thin coating of red iron oxide.

Galena is abundant on the lower level. It regularly accompanies the gold and is an even better indicator of rich shoots than red garnet or ankerite. It occurs with gold in fractures cutting the other minerals and has been found in very thin coatings in parting cracks in the red garnet. In the saprolite, it has been oxidized to cerussite and pyromorphite, which generally accompany the near-surface gold. A small amount of bismuth telluride is found in the galena.

Pyrrhotite is widespread and is locally the most abundant sulphide. It occurs generally in cracks through the quartz or in rounded and corroded grains in the other sulphides. Pyrrhotite may or may not accompany the gold.

Pyrite is locally common but is less abundant than pyrrhotite. Crystals are rare and it generally occurs in massive fine-grained aggregates and layers that resemble marcasite; crystals, however, are common in the wall rock. Pyrite, like pyrrhotite, may or may not accompany the gold and is widely distributed throughout the lode.

Chalcopyrite is found in small grains in much of the sulphide. It occurs in amounts too small to concentrate and may or may not accompany the gold. Magnetite occurs in small grains in much of the ore and is especially common as microscopic inclusions in the garnets. Thin curved plates of ilmenite are found locally in the quartz and ore. Ilmenite inclusions also occur in the garnets. Marcasite occurs in many fractures and seams below the water level. It was probably deposited by descending surface waters. No relation between marcasite and the ores has been determined.

[10] Determined by E. T. Erickson, U. S. Geological Survey.

Almost no work has been done on the mineralogy of the saprolite zone. The material consists mostly of brown and red clay with stringers of quartz and a few seams of manganese and hydrous iron oxides. A few of the more resistant minerals, such as apatite, garnet, staurolite, zircon, and kyanite, may be obtained from this material by panning. Pyromorphite is also found in small greenish-yellow grains.

PARAGENESIS.

The deposition of the coarsely crystalline silicates, carbonate, sulphides, chlorite, and gold is thought to have involved various stages in a more or less continuous process. For purposes of discussion, however, the mineralization is divided into three stages:

1. Early stage, characterized by the formation of coarsely crystalline silicates.

2. Intermediate stage, characterized by the deposition of ankerite, quartz, and pyrrhotite.

3. Final or chlorite-galena-gold stage.

The minerals of the first stage include garnet, kyanite, tourmaline, biotite, muscovite, chrome mica, ilmenite, magnetite, chlor-apatite, cummingtonite, and possibly staurolite. Nearly all these minerals are present in varying amounts in the Carolina gneiss of the surrounding region. The correlative distribution of the coarsely crystalline silicate minerals and the ores and the similarity in composition between the coarse silicates in the lode and the finer silicates in the country rock suggest that the coarse silicates were formed by a recrystallization of already existing minerals and that this recrystallization was caused by fluids that later deposited the ores. Some of the minerals, such as chlor-apatite and possibly others, may have received at least part of their constituents directly from the mineralizing fluid. The fact that the discoidal garnets in the schist are coarser in and near the lode than at a distance indicates that the garnet in the schist may also have some genetic connection with the lode.

The minerals of the first stage are veined by minerals of the second stage or occur in partly resorbed remnants in the minerals

of the second stage. During the second stage, ankerite formed early; later it was brecciated, and the fragments were recemented in a mass of sugary quartz. Locally the quartz is broken, and irregular veinlets and grains of pyrrhotite have formed in the fractures and interstices.

The final stage was a direct continuation of the second stage, but the mineral deposition took place at considerably reduced temperatures and pressures. Small amounts of chalcopyrite were formed early, as the mineral occurs in veinlets through pyrrhotite. Chlorite rims developed around ankerite (Fig. 8), and locally biotite and cummingtonite were partly altered to chlorite. Fine-grained pyrite may have been deposited, although its position in the sequence has not been exactly established. Galena and gold were the last two minerals to form; they occur together in fractures cutting other minerals, and other sulphides are found in small rounded particles in both galena and gold. Particular attention has been directed to the determination of the relative ages of the galena and gold. The two minerals customarily occur together, and many specimens containing them have been examined. No data have been found that would indicate an age difference between these minerals, but Mr. Newton, the mine manager, reports having seen one specimen of galena with a cross-cutting veinlet of gold. The two minerals occur together in small cracks; one mineral will occupy the entire crack, then the other. They are found in small isolated areas in each other and in places are intimately mixed and intergrown. They are considered to be largely contemporaneous.

The mineralization has been to a great extent controlled by cross fractures. These fractures have been reopened at various intervals through the period of mineral deposition. Some cross-fracturing preceded the recrystallization of the silicates, as coarse garnet and micas are seen in many places in veinlets crossing the schistosity (Fig. 4). The garnet-bearing fractures have been reopened and largely recemented by quartz. That the movement did not stop during the mineral deposition is shown by the brecciation of ankerite and its recementation by quartz. Renewed

movement after the quartz deposition is indicated by the fact that the rich ore is localized along seams, in places tight, which have broken the quartz and have later been healed by sulphides and gold. Finally a small amount of post-ore movement occurred, as shown by the local brecciation and smearing of the ore.

The conditions favorable for the deposition of such minerals as garnet and kyanite are ordinarily different from conditions prevailing where chlorite, galena, and gold will form. McLaughlin [11] states that chlorite indicates conditions approaching shallower and lower-temperature deposits. It is probable that at the Battle Branch lode the temperature and pressure of the original fluid had been considerably lowered before the final stages of mineralization. The deposit shows, in a small compact body, minerals deposited at various stages through the deep-vein zone and, in part, under conditions that approach those of the mesothermal zone.

OXIDATION AND ENRICHMENT.

The old hydraulic pits above the present workings furnish good exposures of the lode in the oxidized zone. The lode consists of quartz stringers and lenses in the saprolite. Eldridge,[12] speaking of the quartz in the hydraulic pit, says: "The quartz is cellular, coated partially with oxide of iron. . . . That portion connecting the pockets is usually far more compact and is not nearly as rich in gold as the cellular variety in the pockets, this latter variety presenting universally most beautiful forms of occurrence of coarse gold of a rich yellow luster."

Before the present work was begun the water level was above the collar of the Rogers shaft: water flowed from the shaft. The rock above the water level is thoroughly decomposed, but below it undecomposed remnants become increasingly common to the 85-foot level. At this point, about 80 feet vertically below the surface, the rock is still soft and partly decomposed. This is about the maximum depth of surface alteration, so far as is

[11] McLaughlin, D. H., Hypothermal deposits: Ore Deposits of the Western States (Lindgren volume), pp. 558–559, Amer. Inst. Min. and Met. Eng., 1933.

[12] Eldridge, G. H.: *Op. cit.*

known, and much of the 85-foot level is in hard, unaltered schist. Near the shaft, the soft character of the deeper saprolite changes rather abruptly along a water-bearing fracture; below this fracture the rock appears unaltered. The lower level is in rock that appears entirely fresh except along a few water-bearing fissures.

The supergene enrichment of the gold of the southern Appalachian deposits has been much discussed. The future of many of the mines and prospects depends on whether or not the ores will persist in depth. The Battle Branch mine is at present the deepest accessible mine in Georgia. It is about 220 feet deep on the incline, or 130 feet vertically below the original surface at the lowest point. Efforts have been made to observe any criteria that might point toward a supergene origin of the gold. There is apparently no doubt that the ore near the surface was enriched by the mechanical settling of the gold.

The close association and contemporaneity of the gold and the galena indicate that if the gold of the unoxidized ore is supergene, the galena is also. Galena is generally not considered to be a supergene mineral. The close association of the gold with coarse garnet, kyanite, and micas, and the fact that the quartz bodies widen at the rich shoots may be advanced as evidence against supergene enrichment. The narrow marble bands, ankerite, and sulphides, especially pyrrhotite, in the ores would tend to precipitate gold from solution in the upper zone, if present knowledge of the chemistry of this subject is correct.[13] Some of the ore pockets are blind; they do not outcrop, and the pockets so far found bear no evident relation to the water level. Better ore was obtained in and just above the 173-foot level than was found near the 85-foot level. The fact that the sulphides, even in the deeper workings, contain almost no gold also indicates that gold has not been derived from overlying leached sulphide bodies.

Eldridge[14] states, after T. R. Lombard, a former operator, that " In the pockets of the upper part of the mine the upper parts

[13] Emmons, W. H.: The Enrichment of Ore Deposits. U. S. Geol. Survey Bull. 625, pp. 305–324, 1917.

[14] Eldridge, G. H.: *Op. cit.*

of the lenses were the richest, both in quantity and quality." The depth attained is hardly enough to be conclusively below the zone of possible supergene enrichment; considerable marcasite, probably of supergene origin, is present. The ores are associated with fractures along which downward-percolating waters easily circulate. Appreciable amounts of manganese and chlorine, the two elements usually considered necessary for the solution of gold in nature, are present in the ores. Gold from the oxidized ore is generally of a finer grade than the deeper material. This indicates that some solution of silver has probably occurred in the upper ores but does not necessarily indicate any solution of the gold. The fact has already been mentioned that in one ore shoot the gold dipped at a slightly steeper angle than the quartz band.

Although it is likely that the gold in the upper part of the saprolite zone was enriched mechanically, and possibly also chemically, the conditions set forth above preclude the possibility of such enrichment at depth. The deeper gold ores are considered to be of hypogene origin, not reworked nor enriched by descending solutions.

CONCLUSIONS.

The Battle Branch lode is a zone of silicified and mineralized schist with numerous quartz lenses and stringers. Fracturing across the lode occurred at intervals during its formation, and this continuing movement controlled to a considerable extent the deposition of the ores. Small shoots of high-grade gold ore are localized where quartz bands in the lode are intersected by joints and fractures.

The mineralogy of the deposit is unusual. Three stages are distinguished. The first was characterized by the formation of coarsely crystalline silicates, especially garnet, cummingtonite, kyanite, and micas. These silicates were probably formed by recrystallization of minerals in the wall rock, the recrystallization being brought about by the fluids that later deposited the ores. During the second stage, ankerite, quartz, and pyrrhotite were deposited. The third stage was characterized by the depo-

sition of chlorite, galena, and gold under conditions that approached those of the mesothermal zone.

The soil and saprolite extend to a maximum depth of about 80 feet. Mechanical enrichment of the gold has occurred in the saprolite. The available evidence indicates that the galena and gold in the rich shoots are contemporaneous and of hypogene origin.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
Oct. 2, 1935.

GEOLOGY AND ORE DEPOSITS OF THE CENTRAL PATRICIA GOLD MINE,[1] ONTARIO.

J. M. CORMIE.

INTRODUCTION.

PICKLE Lake is situated in the district of Kenora (Patricia Portion), Ontario, 85 miles north of Allanwater on the main line of the Canadian National Railway, and about 125 miles northeast of Sioux Lookout. It is 25 miles north of the east end of Lake St. Joseph. The Kawinogans (Crow) River rises southwest of Pickle Lake, flows northeasterly, and uniting with the Otoskwin River, reaches James Bay. Pickle Lake lies about one and one-half miles south of the Crow River, and drains into it by way of a small creek. The Central Patricia Mine is located on the south bank of the Crow River, two and one-half miles east of Pickle Lake.

The ore bodies of the Central Patricia Mine are unusual in that they occur in a band of iron formation, fractures in which are filled with pyrrhotite, arsenopyrite, chalcopyrite, pyrite, quartz, carbonates, and chlorite. Original material of the iron formation has also been partially replaced by these minerals. Gold is associated with the sulphides but its exact relationships are unknown.

Areal geological work in this district is limited to that done by W. McInnes, of the Geological Survey of Canada,[2] and by M. E. Hurst, of the Ontario Department of Mines.[3]

The discovery of the mineral deposits of the Pickle Lake-Crow River area is comparatively recent, due to its remoteness, but airplanes have made the district easily accessible, and most of the belt within which gold occurrences are known was staked in 1928. At that time the Connell Mining and Exploration Com-

[1] Published by permission of the Central Patricia Gold Mines, Limited.

[2] Annual Report, Geol. Survey of Canada, vol. XVI, 1904, Pt. A, pp. 154–158.

[3] Ontario Department of Mines, vol. 39, Pt. II, 1930.

pany acquired several groups of claims, on one of which the Central Patricia Gold Mine property is located.

Trenching and diamond drilling encountered commercial gold ore, some of which was very high-grade. A program of underground development work was commenced in 1929 and continued until the fall of 1930, when the property was closed. By that time a three-compartment shaft had been sunk to a depth of 525 feet, a total of nearly 2,000 feet of drifting had been done on four levels, and a large number of short cross-cuts completed.

The increased price of gold during 1932–33 enabled the property to be reopened, and in May, 1934, milling began at the rate of 50 tons per day and is now increased to 110 tons per day.

GENERAL GEOLOGY.

All the rocks of the area are of pre-Cambrian age. The general geology is summarized in the following table:

Quaternary	Pleistocene	Glacial sands, clays and gravels.
	Great Erosional Unconformity	
Pre-Cambrian	Keweenawan	Diabase
	Intrusive Contact	
	Algoman	Introduction of quartz veins and sulphide bodies?
	Intrusive Contact	
	Pre-Algoman intrusives	Diorite and gabbro—imperfectly distinguished from the Keewatin.
	Intrusive Contact	
	Keewatin	Quartz porphyry?, iron formation, greenstone.

The greenstones are the oldest as well as the most widespread rocks of the area. They are chiefly basic lavas, varying from andesite to basalt, but in specimens taken near the mine, the original minerals cannot now be recognized. A zone of shearing passes through this area, and all rocks with the exception of the iron formation have been altered to chlorite and sericite schists.

The lavas are similar lithologically and in their relation to the other rocks, to those called Keewatin in other areas. Since no other criteria are available they are tentatively called Keewatin.

Rhyolite occurs at a few places in the belt. A short distance north of the ore zone there are bodies of quartz porphyry altered to porphyritic quartz-sericite schists. These are thought to be intrusive by certain observers, and have even been assumed to be connected with the deposition of the ore. As yet no conclusive evidence of intrusion has been found. The bodies of quartz porphyry are probably porphyritic, acid, Keewatin flows.

Bands of iron formation are found here and there in all parts of the district, intercalated with the Keewatin lavas. They vary in thickness from a foot to two hundred and fifty feet. Some are continuous along the strike for several hundred feet; others are short lenses. The one in which the ore bodies of the Central Patricia Mine occur is on the south bank of the Crow River. It strikes nearly east-west. In a distance of 1,800 feet along the strike there are three lenses, each about 400 feet long, separated from each other by greenstone schist. The maximum width is fifty feet. Iron formation consists of layers of silica alternating with layers either of magnetite, of iron carbonate or of mixtures of these. Generally the carbonate is more abundant than the oxide. Individual bands or laminæ vary in width; the maximum is about three inches.

About one-half mile east of the shaft of the Central Patricia Mine, a diabase dike of northwest strike cuts the greenstones. It is massive and unaltered, and is the youngest consolidated rock.

These are the only rock types found in the immediate vicinity of the mine, but bodies of gabbro or diorite, which appear to be intrusive into the greenstone, occur in the area. They are mostly

less altered and appear to be later dikes. As yet no attempt has been made to map them separately. Granite outcrops about a mile north and the same distance south of the mine. Following the general usage, it has been called Algoman.

Structure.—The rocks in the vicinity of the Central Patricia Mine strike N. 50° E. to N. 75° E., and dip steeply to the northwest. They probably represent the north limb of a large anticline, the eroded axis of which lies an unknown distance to the south.

The greenstone and quartz porphyry have been sheared, and in places have a schistosity, the strike of which is about N. 50° E., either parallel to the strike of the rocks or intersecting it at a low angle. For this reason displacements parallel to this direction are not easily recognized. So far none of any magnitude have been found.

Cross-fractures strike northwesterly and dip to the northeast. These are apparently tension fractures that were later filled by ore minerals. Cross-fracturing is best developed in the iron formation; it is not generally noticeable in the greenstones. The effects of shearing stresses, on the other hand, are conspicuous in the greenstone and quartz porphyry.

The reactions of different rocks to shear and tension seem to be due to relative differences in brittleness. The greenstone flowed like plastic material, whereas the more brittle iron formation fractured. Thus, the cross-fractures in the iron formation disappear on passing into greenstone.[4]

At the east end of the underground workings, on the first and second levels, the iron formation is cut off sharply and the drifts enter fractured greenstone. This may be due to faulting, but there is also a possibility that it is merely the continuation underground of the discontinuity in the iron formation that can be seen on the surface.

[4] Hurst, M. E.: *Op. cit.*

ECONOMIC GEOLOGY.

General Statement.

The ore bodies of the Central Patricia Mine are sulphide-rich masses, which were formed by fracture-filling, and by replacement of iron formation. Pyrrhotite and arsenopyrite are the predominant sulphides; chalcopyrite and pyrite are less abundant. Non-metallic minerals present are quartz, chlorite and carbonate. Gold is the only economically valuable mineral in the ores; silver is present, but in minor quantities.

The iron formation here dips northwards at about 75°. The ore occurs in shoots in it, which rake to the east at 60°. Three of these are known, all of which outcrop west of the shaft. Immediately east of the shaft there are surface indications of another body of ore. The *A* ore shoot, the smallest and easternmost of the three known ore bodies, has not been found below the second level. The two main shoots continue to vertical depths of 500 feet, which is the lowest level yet reached in the mine. They still maintain their size and grade at that depth. The two larger ones—*B* and *C*—average between 75 and 100 feet in length along the drifts but are very irregular. Stoping has shown that the sulphide zones swell and pinch markedly, particularly in the *C* ore body.

Mineralogy of the Ores.

General Description.—The sulphides found in the ore in order of abundance are pyrrhotite, arsenopyrite, chalcopyrite and pyrite. The two latter are present in such small amounts as to be negligible; chalcopyrite has never been recognized in hand specimens. Gold has not been found in particles large enough to be visible except under high magnifications. The nonmetallic constituents of the ore are quartz, carbonate, and chlorite. There are also quartz veins, and stringers of quartz and calcite. Much of the vein quartz is black, but white quartz and black commonly occur in the same specimen. The black variety has been found only in veins and stringers within the ore bodies.

The character of the mineralization differs in the different

shoots. In the *B* ore body, pyrrhotite is the predominant sulphide. Arsenopyrite is present, but in subordinate amount. This ore body differs from the others in the small amount of arsenopyrite and the large amount of chloritic material present in it. In places chlorite is the most abundant mineral constituent but usually there is less chlorite than quartz and carbonate.

The most noteworthy feature of the *C* ore body is the abundance of arsenopyrite, which appears to be almost equal to the pyrrhotite in quantity. In places pyrrhotite or gangue are almost lacking and the ore consists of coarsely crystalline arsenopyrite, with grains up to one-half inch in diameter. Arsenopyrite is more abundant in the central part of the sulphide zone; pyrrhotite, with the few exceptions mentioned above, is present throughout. It extends beyond the arsenopyrite zone, and becomes the only visible sulphide on the margins of the ore body, where tiny stringers of it extend out into unmineralized iron formation. The nonmetallic minerals present are the same as those of the *B* ore body, but there is much less chlorite and carbonate.

Metasomatic replacement is as important as fissure-filling, and in the *C* ore shoot more of the ore seems to be due to replacement than to any other process. In this shoot, the ore minerals have penetrated the iron formation parallel to the banding, and have replaced the silica, iron oxide and carbonate. The replacement was in part selective, controlled, apparently, by the character of the iron formation. It is quite common to find a single band completely replaced by sulphides, and neither of the adjacent bands affected. The silica laminæ have been replaced more readily than those containing iron. Where replacement has affected all the host rock it is still possible in places to recognize the original banding by a rude zoning of the sulphides, by the fact that the pyrrhotite in adjacent bands varies in texture, or by the presence of streaks of chloritic material in the sulphides. The chloritic seams may be fairly continuous and regularly spaced, or only traces may be left. The distance between the chloritic zones is of the same order as the width of the laminæ of the iron formation. It is probable that they represent layers that were originally

rich in iron minerals. Where arsenopyrite is the predominant sulphide, residual structures are absent. Where pyrrhotite is present, either alone or in appreciable amount with arsenopyrite, the original structure of the iron formation is retained.

Microscopic Characteristics.—Microscopic examination of samples of the ore in polished and thin sections shows the following characteristics.

Pyrrhotite occurs as shapeless anhedrons in and around arsenopyrite crystals, and in patches and shreds in the gangue. In polished section it has a brownish-gray color, and commonly is spotted with nonmetallic minerals, usually chlorite. Pyrrhotite follows lines of weakness, and in sections cut in proper orientation from replaced iron formation, it is usually to be seen following the banding (Fig. 1).

Arsenopyrite occurs in definite crystals, which may be so numerous that they constitute 80 per cent. or more of the ore. The outlines of many crystals are modified by replacement by later minerals, so that the borders are embayed. Commonly there is also replacement within the grains (Fig. 2). The crystals of arsenopyrite are found to have a random orientation in the host rock, regardless of its structure. This difference in the habits of arsenopyrite and pyrrhotite may be seen in the same section. Pyrrhotite occurs in trains of small grains, apparently parallel to the banding of the iron formation. In contrast to this, arsenopyrite is in large, blocky crystals lying athwart the streaks of pyrrhotite. In places pyrrhotite continues through the obstructing crystals of arsenopyrite.

Chalcopyrite may occur alone, but commonly it occurs in small, irregular blebs in intimate association with pyrrhotite. It is sparse but widely distributed. Pyrite is rare, in isolated masses in fractures and vugs and not generally associated with other sulphides. It is usually well crystallized.

Gold seems to be associated with all the sulphides except pyrite, but very little of it is visible under the microscope. It has been seen with an objective of medium power, but not more than a dozen grains were found in all the sections examined, even using

magnifications up to 900 diameters. The largest seen was 0.02 mm. in diameter. Since these sections were taken from high-grade specimens, it is evident that gold is present either in particles

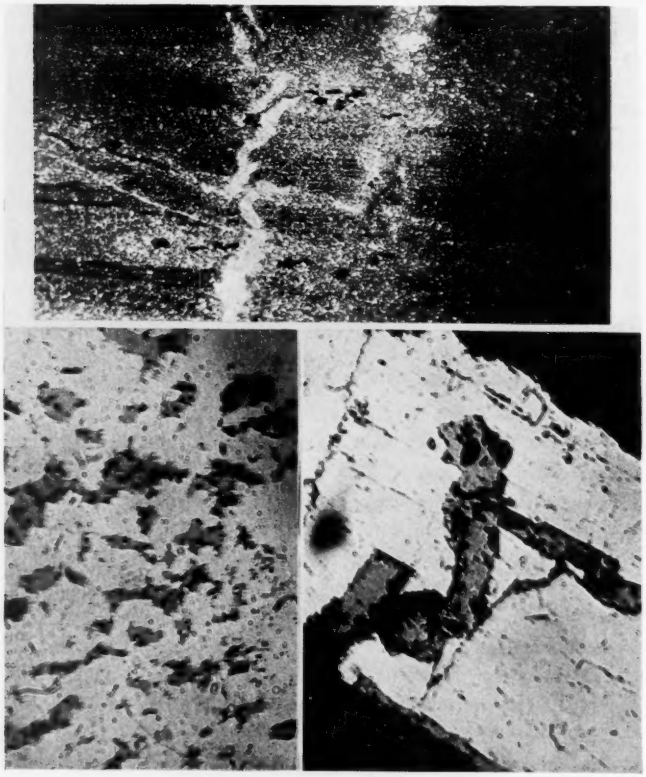

FIG. 1. Fractured iron formation. Fracture-filling is carbonate and sulphide. Sulphides are also seen to have penetrated the iron formation parallel to the banding. × 25.

FIG. 2. Replacement of arsenopyrite (light gray) by pyrrhotite (darker gray) and nonmetallics (black). × 80.

FIG. 3. Pyrrhotite and nonmetallics filling fractures in arsenopyrite. × 95.

so fine as to be invisible with the magnifications available, or in some other physical or chemical state. The grains that were seen occurred alone in the arsenopyrite or were associated with pyrrhotite.

Quartz is associated with the chlorite and carbonate in the ore, and also occurs in later veins. In the ore it forms mosaics. Chlorite is one of the characteristic minerals of the ore bodies, particularly in the *B* shoot. It is a green pleochroic variety with an ultrablue interference color, and is probably an iron-rich variety.[5] It occurs in shapeless masses and shreds, irregularly distributed among the other minerals. Apparently there are two kinds of carbonate. One type is in rather small grains, of which both indices of refraction are greater than those of quartz, and is probably an iron carbonate. The other type is in large crystals, which show twinning lamellæ, and have one index of refraction about equal to that of quartz. Hence, it belongs in the calcite-magnesite group.[6]

Paragenesis.—The most obvious feature of the age relationships of the various minerals is the fact that the arsenopyrite crystals have been extensively fractured, and the fractures have been filled by pyrrhotite, chalcopyrite and nonmetallic minerals (Fig. 3). The edges of crystals have been replaced by pyrrhotite and replacement has also taken place in the interior of the arsenopyrite crystals, apparently independently of any visible fracturing (Fig. 2). In such cases there are irregular blebs of pyrrhotite, chalcopyrite and gangue in the arsenopyrite crystals, and almost all stages of replacement are to be found.

Chalcopyrite and pyrrhotite have mutual boundaries, and no evidence was found showing a difference in age. They are believed to be contemporaneous.

Pyrite is obviously later than both the other sulphides and the gangue. It generally occurs in fractures not associated with other minerals, but one specimen was examined in which it was seen to have replaced arsenopyrite.

The nonmetallic minerals of the ore are intimately associated

[5] Winchell, A. N.: Elements of Optical Mineralogy, Part II, p. 282.

[6] *Idem*, p. 69 et seq.

with pyrrhotite and chalcopyrite and, like them, are younger than arsenopyrite. Pyrrhotite commonly contains particles of nonmetallic minerals, particularly chlorite, but the age relations are not clear, nor are those between the three common nonmetallic minerals present in the ore bodies.

The mineral succession is: Pyrite, quartz veins; fracturing; pyrrhotite, chalcopyrite and gangue; fracturing; arsenopyrite; fracturing. It will be noted that three periods of fracturing are indicated. That number has been definitely recognized, but the process may have been continuous rather than confined to definite periods separated by intervals of quiet deposition.

Genesis of the Deposit.

The mineral deposits of the Central Patricia Mine have been shown to occur in fractured and replaced iron formation. The character of the solutions can be inferred from the minerals that are present.

Arsenopyrite, pyrrhotite, and commonly iron-rich chlorite, are high-temperature minerals,[7] and their presence indicates that in the early stages of deposition the solutions were at a fairly high temperature. On the whole, the mineralogy of the ores seems to correspond with those classed by Lindgren as hypothermal.

The mineralization at the Central Patricia Mine cannot be assigned to the intrusion of any particular igneous mass, but there are three possible associations: (1) The largest body of igneous rock in the region is the granite batholith which outcrops one mile south of the mine. It seems reasonable to believe that the magma from which such a mass formed could have been the source of solutions capable of forming the ores of the Central Patricia Mine. (2) If the quartz porphyry is an intrusive rock, it may be genetically connected with the source of mineralization, though by itself it seems unlikely that it could have produced the ore bodies. It may, however, be part of a larger mass which is not exposed in the immediate vicinity. It is not mineralized, and no sulphide deposits have been found directly associated with it. (3) The

[7] Lindgren, W.: Mineral Deposits, p. 637 et seq., 1933.

diabase dike is probably small and does not seem to indicate any large intrusive mass, although, like the quartz porphyry, it may be merely the surface exposure of a larger body of igneous rock. It is not known to have produced any mineral deposits.

The mineralization is associated with openings formed as a result of the folding and buckling of the Keewatin rocks. The relatively brittle iron formation was fractured, and openings were formed along which the ore-bearing solutions could later penetrate. Open fracturing did not extend into the less brittle greenstones on either side of the band of iron formation. Hence, there are no ore bodies in the greenstone and only a local impregnation of the schist near the ore zone. The ores have been formed in part by deposition in openings, in part by replacement of the original minerals of the iron formation.

QUEENS UNIVERSITY,
KINGSTON, CANADA,
May 25, 1935.

THE AGE RELATIONS OF THE WARD ORES, BOULDER COUNTY, COLORADO.

ERNEST E. WAHLSTROM.

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INTRODUCTION.

WITH the intention of trying to determine the relative ages of the ore deposits of the Ward District, Boulder County, Colorado, and the Tertiary (?) igneous intrusions, the writer examined several of the mines and discovered several problems in local ore genesis. It is the purpose of this paper to describe briefly some of these problems and to attempt reasonable explanations.

A brief summary[1] of the geology of the district follows: With the exception of the alluvial and glacial deposits, all the exposed rocks are either igneous or metamorphic. The nearest unmetamorphosed sediments lie along the east flank of the Front Range of the Colorado Rockies, about ten miles east of the area under discussion. Pre-Cambrian schists, gneisses, granites and quartz diorites comprise about two thirds of the exposed rocks.

The occurrence of most of the important Colorado mining districts in a roughly delineated belt extending from southwestern Colorado northeasterly to Boulder County has been noted by several authors, notably Spurr and Garrey,[2] and Bastin and Hill.[3]

[1] Adapted from report by P. G. Worcester, Geology of the Ward Region, Boulder County, Colorado. Colo. Geol. Survey, Bull. 21, 1921.

[2] Spurr, J. E., Garrey, G. H., and Ball, S. H.: U. S. Geol. Survey, Prof. Paper 63, pp. 67–71, 1908.

[3] Bastin, E. S., and Hill, J. M.: U. S. Geol. Survey, Prof. Paper 94, p. 93, 1917.

The paragenesis of the ores has been worked out for many of the districts, and some attempts have been made to correlate specific ore occurrences with local igneous intrusions.

Spurr,[4] in his description of the Stanley Mine in the Georgetown District, has noted that a dike of biotite latite porphyry cuts the Stanley vein and is therefore younger. The vein, in turn, cuts an intrusion of bostonite. According to Bastin and Hill,[5] the vein in the Bluebird Mine in the Nederland District, Boulder County, Colorado, is cut by a dike of andesite porphyry. The Nederland District is only a few miles south of the area described in this paper.

The Ward District is near the northern end of the Colorado mineral belt and is well suited to the investigation of the genesis of the ore deposits because of the close association of the ore deposits with Tertiary (?) intrusions.

TERTIARY (?) INTRUSIONS.

The Tertiary (?) intrusions (Fig. 1) occur as a number of dikes and small stocks whose distribution suggests that they have a common origin. Hand specimens and thin sections from the individual stocks confirm this suggestion.

The principal rocks of the stocks are classified by Worcester[6] as monzonite porphyry and diorite porphyry. Thin sections show small amounts of free quartz. The dike rocks are felsite porphyry of the same general composition as the monzonite and diorite porphyries, but in some places they contain sufficient free quartz to be classified as dellenite porphyry and dacite porphyry.

The diorite porphyry appears to be closely related to the monzonite porphyry. In places a single intrusion will show gradations between the two types. Although the rocks are referred to as diorite porphyry and monzonite porphyry, they grade in places into andesite porphyry and latite porphyry, particularly at the borders of the intrusions. In all the specimens there is a dense to fine-grained groundmass, but since the phenocrysts

[4] *Op. cit.*, pp. 343–344.
[5] *Op. cit.*, pp. 101 and 185.
[6] Worcester, P. G., *op. cit.*

average from 40 to 50 per cent. of the rocks by volume, the terms diorite porphyry and monzonite porphyry are properly used.

Some of the dikes in the vicinity of the monzonite porphyry stocks are older than the porphyry. The dikes of dense to por-

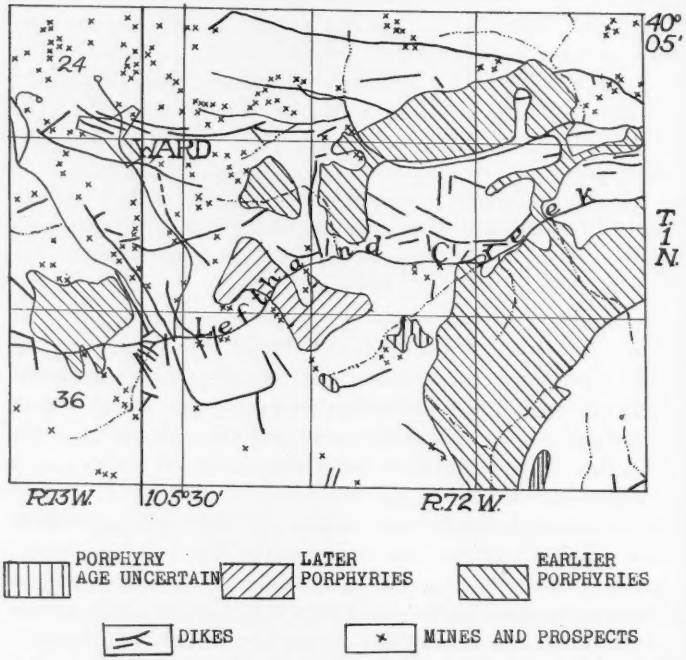

FIG. 1. Outline map of the Ward District, Boulder Co., Colo., showing distribution of mines, prospects, Tertiary (?) dikes and porphyry stocks. The country rock is pre-Cambrian schists, gneisses, and granite. The porphyries are dated with respect to the quartz-pyrite-chalcopyrite ore. (Adapted from map by P. G. Worcester. Assignment of ages of porphyries is by the present writer.)

phyritic felsite probably were formed from magma moving along cracks in advance of the main body of magma. Later, as the main body moved into place to form the stocks, the earlier-formed

dikes were transected. It is possible that some of the dikes were formed after the emplacement of the main part of the magma.

THE ORE DEPOSITS OF THE WARD DISTRICT.

The predominant mineralization is auriferous quartz-pyrite-chalcopyrite ore; some ores contain also small amounts of molybdenite, wolframite, sphalerite, and specularite. In one mine, in addition, important amounts of galena-silver-carbonate ore occur.

The writer believes that the gold-copper ore was deposited from solutions that came from the same magma chamber which gave rise to the Tertiary (?) intrusives, and that the ore was deposited under conditions of medium to high temperature and high pressure. The association of quartz, pyrite, and chalcopyrite is characteristic of mesothermal deposits, but the presence of wolframite, molybdenite, and specularite suggests that the temperatures approached those of hypothermal deposits.[7] This is supported by the fact that the quartz in the veins resembles pegmatitic quartz. The absence of cavities in the undisturbed veins, and the usual sharp demarcation of the vein walls, suggest that the veins were formed under medium to high pressures. The veins are continuous along both strike and dip; in some places veins may be traced at the surface for several thousand feet.

Most of the commercial deposits are of the gold-copper type but the White Raven mine is a notable exception. Originally starting upon gold-copper ore, it has, since 1913, yielded silver-lead ore, to the value of about $800,000.

The ores of the White Raven mine consist chiefly of argentiferous galena and native wire-silver in a gangue of manganiferous siderite, barite, and chalcedonic quartz deposited in the interstices between rounded boulders in a brecciated zone. Its minerals are characteristic of deposits formed under conditions of low to medium temperature. The fact that the breccia contains large vugs indicates that the minerals were deposited at low pressures. Throughout the vein the material cementing the in-

[7] Lindgren, Waldemar, Mineral Deposits, 3rd Ed., p. 599, 1928.

dividual fragments of the breccia consists only of loosely interlocking crystals of the ore minerals.

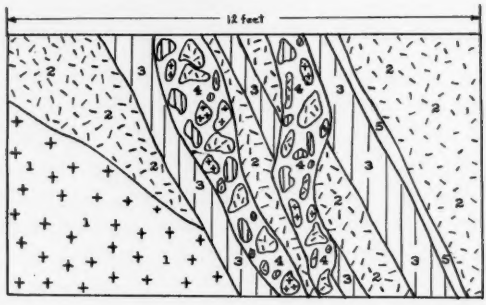

FIG. 2. Ideal cross-section of White Raven vein, Ward, Colo., showing age relations of ores and country rock. (1) Pre-Cambrian granite, (2) Tertiary (?) dellenite porphyry, (3) gold-copper ore, (4) silver-lead ore containing brecciated fragments of granite, dellenite porphyry, and quartz-pyrite-chalcopyrite ore, (5) gouge.

The veins of the Ward District all occur outside of the porphyry stocks. Most of the important mines are located in or near the mining town of Ward. Many other mines in the district occur near the peripheries of the stocks, indicating the probability of the existence of a large body of igneous rock beneath the area near Ward. There may have been numerous veins in the country rock above the present stocks before they were exposed by erosion.[8]

The absence of veins in the porphyry stocks may be due to the fact that the porphyries are dense and resistant and probably did not fracture readily. The movements of the ore-bearing solutions were confined to the peripheral zones of the porphyry stocks and to dikes and fractures in the country rock.

Structure and Paragenesis of the Ore Deposits.

The gold-copper ore occurs in fissure veins and as replacements in their walls. Some of the profitably worked veins are only

[8] See diagram by B. S. Butler, ECON. GEOL., vol. 10, p. 119, 1915.

a few inches wide; other veins are locally as much as seven or eight feet wide, as in the Columbia and Adit mines. The veins locally consist of a number of closely spaced parallel veinlets and have the appearance of sheeted zones. In some mines, the boundary between vein and wall rock is sharp; in others, the wall rock has been mineralized, and the quartz, pyrite, and chalcopyrite form irregular replacement deposits within a few feet of the vein.

Most of the veins are compact; some are crudely banded. The distribution of the minerals is ordinarily irregular; the chalcopyrite and pyrite occur in intimately mixed masses in the massive, glassy-appearing vein quartz; sphalerite, molybdenite, wolframite, and specularite occur in small amounts in only a few mines.

The minerals of the silver-lead vein in the White Raven mine occur as layered incrustations in vugs produced by the movement along an older gold-copper vein. Shattering of the older vein and country rock has produced in places a well defined breccia. The breccia contains rounded fragments of both wall rock and gold-copper ore, cemented by crystallized masses of galena, barite, and carbonate. In places the breccia resembles a sedimentary conglomerate.

The rounding of the pebbles has apparently been produced by the mutual abrasion of the fragments in the breccia during repeated periods of movement along a fracture zone which may have been due to the intrusion of the large bodies of porphyry in the vicinity of the vein. The maximum movement nowhere exceeds 30 feet.

The solutions that deposited the silver-lead ore varied in chemical character, as is shown by study of specimens. The ore is banded and displays the following succession: chalcedonic quartz, manganiferous siderite,[8a] barite, galena, manganiferous siderite, galena, wire silver. The wire silver may have been formed by oxidation or reduction of argentite.[9] The appearance of carbonate and galena in two generations may be the result of a renewal of igneous activity near the source of the mineralizing

[8a] Determined by chemical analysis.

[9] Kohlschutter, V., and Eydmann, E.: Liebig's Annalen der Chemie, vol. 390, pp. 340–364, 1912.

solutions. That the variations in the solutions were not constant is further shown by the banding in the individual layers of carbonate (Figs. 3 and 4).

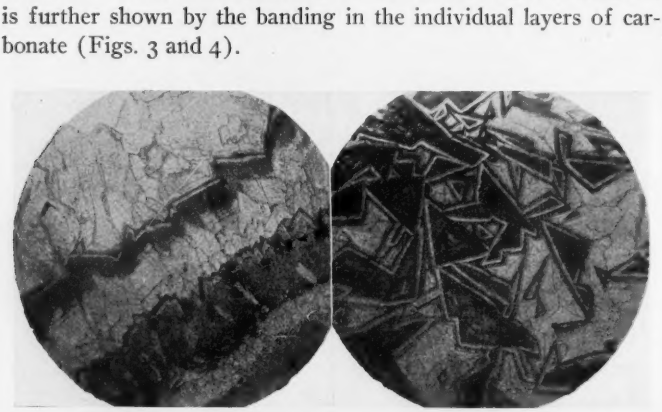

FIG. 3 (left). Thin section cut across carbonates in silver-lead vein, White Raven mine, Ward, Colo. The carbonate is manganiferous siderite. The carbonates in the darker layers contain small amounts of oxides of iron and manganese. The small black patches are galena. ×9.

FIG. 4. (right). Thin section of carbonates in White Raven mine, Ward, Colo. Section is cut parallel to vein and shows in detail the banding in the carbonate, produced by marked variations in solutions from which minerals were deposited. ×6.

The gold-copper solutions produced silicification, sericitization, and kaolinization of the wall rocks. In places, the alteration extends several feet into the walls. Many of the porphyry dikes are slightly mineralized by pyrite, and contain much sericite. The silicification of the wall rock has produced irregular, glassy-looking masses of quartz that resemble pegmatitic quartz. Kaolinization is widespread in all the veins that were examined.

Age Relations of the Ores.

Some paragenetic relations have already been pointed out. Gold-copper and silver-lead ores, in a single vein, cut a dike of dellenite porphyry in the White Raven mine, proving that both ores are later than this intrusion. It is known that the silver-

lead ore is later than the gold-copper ore (Fig. 2). The White Raven vein contains brecciated fragments of gold-copper ore embedded in a matrix of the minerals of the silver-lead ore. The relations of the ores to each other and to the country rock are diagrammatically represented in Fig. 2. Gold-copper ore also cuts a dike of dellenite porphyry in the Philadelphia mine.

Several mines on the peripheries of the stocks of monzonite porphyry were examined in an attempt to date the ore with respect to the monzonite porphyry. In one, the Parole, it was found that a fault zone containing gold-copper ore cuts monzonite porphyry as well as the granite country rock. Although the main metallization is in the granite about 200 feet from the monzonite porphyry, the intervening part contains stringers and veinlets of ore. The porphyry near the vein is considerably kaolinized and contains a few small seams of quartz and pyrite. The kaolinization decreases markedly away from the seams. This suggests that the same solutions that effected the deposition of the quartz and pyrite were also active in the kaolinization.

About a mile southeast of the town of Ward, Worcester [10] has mapped a small body of porphyry as diorite porphyry. The diorite closely resembles the monzonite porphyry and is probably related genetically to it. A small prospect tunnel on its border discloses the relative ages of ore and intrusion. There, a solid vein of quartz and pyrite has a hanging wall of porphyry and a footwall of granite; the porphyry, dense at the vein wall, grades outward into coarser porphyry; apparently it is " frozen " to the vein. Specimens of it with small angular inclusions of gold-copper ore were picked up on the dump. The same relations were discovered in a small prospect 100 yards east of the portal of the Moltke tunnel. These observations indicate that the gold-copper ore is earlier than the diorite porphyry intrusion.

The possible connection between this intrusion and the deposition of the silver-lead ores of the Ward District is suggested by the following facts: The silver-lead ore is later than the gold-copper ore, as is the diorite porphyry intrusion. Several mines,

[10] Worcester, P. G., *op. cit.*

especially the Blue Coat, the Moltke, the Bismarck, and the Ward cross-cut tunnel, are near the periphery of the diorite porphyry intrusion and contain silver-lead ore. The White Raven and Black Jack mines are about a half-mile away from the intrusion but are on the same vein as that in the Blue Coat mine. This vein occupies a fracture zone that extends to within two or three hundred feet of the porphyry, where it is concealed by the alluvium. It is to be emphasized that the silver-lead ore does not occur near any of the other porphyry stocks in the Ward region.

It is difficult, as in the case of the gold-copper ore, to say whether the silver-lead ore is contemporaneous with or later than the porphyry intrusion. It is known, however, that this type of ore has not been found within the boundaries of the porphyry intrusion. If the ore is later than the intrusion, its absence in the porphyry may be explained by the lack of fissures and cracks in the porphyry. It can only be said that the silver-lead ore is apparently related genetically to the intrusion of the diorite porphyry. It may be that the peripheral zone of the porphyry intrusion acted merely as a passageway for the mineralizing solutions and that the solutions came from depth.

In the east drift of the main level of the White Raven mine the writer observed a narrow dike of dense to glassy, much altered felsite intruded into the vein. The dike ranges in thickness from a few inches to two or three feet. The felsite contains brecciated fragments of granite and quartz-pyrite-chalcopyrite ore, and is distinctly later than both the granite and ore. Moreover, the felsite is cut by numerous veinlets of manganiferous siderite, the gangue mineral of the galena-silver-carbonate ore. The felsite may be an offshoot of the diorite porphyry stock, or, if not, it is probably simultaneous with the diorite porphyry. If the felsite and diorite porphyry are so related, it is evident that the galena-silver-carbonate ore is later than the diorite porphyry.

A study of the White Raven ores gives some idea of the time interval between the intrusions of the different porphyries. The mine contains both types of ore. Wherever the undisturbed gold-copper ore is found, it forms compact, dense veins which were

probably formed under conditions of intermediate pressure and at a depth of from 4,000 to 12,000 feet.[11] The association of this ore with fine-grained porphyries would indicate no greater depth. The association of wolframite, molybdenite, and specularite with this type of ore in other mines of the Ward District indicates a high temperature at the time of deposition.

On the other hand, the silver-lead ore shows evidence of having been deposited at a low pressure and temperature. This ore occurs characteristically as linings in vugs that in many places are more than a foot across. Galena, native silver, and carbonate are characteristic of many low-temperature deposits. The differences in pressure of formation of the two types of ore may be explained by assuming the erosion of several thousand feet of the surface rock above the vein. If the ore deposition followed the intrusion of bodies of porphyry, it is evident that the period of time between the intrusion of the earlier and later porphyries was very long.

CONCLUSIONS.

Field observations disclose the following relations: The porphyries of the Ward region are similar in composition and general appearance. The ore seems to be related intimately to the intrusion of these porphyries. The porphyry bodies probably did not supply the solutions but created channels for the circulation of solutions that came from depth. Not all of the porphyries are of the same age; some are earlier and some are later than the gold-copper ore. Although some of the most productive mines in the district are not near any large exposed body of porphyry, it is probable that such a body exists at depth.

The writer believes, as does Worcester,[12] that all the porphyries and ore deposits had a common source and that the slight differences in composition and texture of the various porphyry bodies are the result of peculiarities of cooling and differentiation. That the source-magma might have been quartz-bearing is suggested by the presence of quartz in some of the dikes and the presence of small amounts of quartz in the rocks of the stocks.

[11] Lindgren, Waldemar: *Op. cit.*, p. 598.

[12] Worcester, P. G.: *Op. cit.*, p. 28.

Localization of the silver-lead ore in the vicinity of a diorite porphyry intrusion indicates the genetic relation of this type of ore to the intrusion. It is believed that the ore is later than the intrusion.

The existence of ore apparently formed under conditions of medium to high pressure and ore formed at low pressures in the same mine may possibly be explained by assuming a period of erosion between the periods of deposition of the two types of ore. The sequence in the Ward District seems to be as follows:

1. Intrusion of dike rocks from monzonitic magma. Fractures associated with the dikes later acted as channels for the circulation of mineralizing solutions.

2. Intrusion of small stocks of monzonitic composition and solidification to latite porphyry, monzonite porphyry, and associated types.

3. Faulting of country rock and, in some places, of the monzonite porphyry. These faults may have existed in the country rock before intrusion, and were reopened after intrusion.

4. Mineralization of the fault zones by quartz, pyrite, and chalcopyrite, and in some mines sphalerite, wolframite, and specularite in addition. This stage also included silicification and sericitization of the wall rocks. Medium pressure and high temperature.

5. Period of erosion.

6. Intrusion of small stock of porphyry.

7. Mineralization of reopened fault zones and veins in vicinity of porphyry stock by chalcedonic quartz, barite, galena, and silver. Pressure and temperature low.

The writer wishes to acknowledge his debt to Dr. R. D. Crawford and Prof. W. O. Thompson for reading this manuscript, and to Dr. P. G. Worcester for permission to use his specimens and map of the Ward District.

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DISCUSSION AND COMMUNICATIONS

HIGH-TEMPERATURE MINERAL ASSOCIATIONS AT MODERATE TO SHALLOW DEPTH.

Sir: In the May number of this Journal, Doctor Buddington [1] presented an interesting paper on the classification of ore deposits in which he especially emphasizes the idea which has been increasingly apparent that near-surface deposits may have been, and a goodly number probably were, formed at relatively high temperature. For such deposits he suggests the name xenothermal deposits, meaning strange, different, or foreign temperature deposits. Before proposing the term and by examples after proposing it, he shows clearly that there is nothing strange, different or foreign about such deposits but that they are a type to be expected, and that they occur in considerable number and variety. Why then call them strange, different, or foreign temperature deposits?

Professor Lindgren made his first general classification of ore deposits on the basis of depth of formation—shallow, intermediate and deep. Recognizing that temperature is probably a more fundamental factor than depth, he changed to temperature of formation, epithermal, mesothermal, and hypothermal. In this change he has been followed by most geologists in form, but not so completely in fact. Instead of changing from depth classification to temperature classification there has been a tendency simply to shift shallow to epithermal, intermediate to mesothermal, and deep to hypothermal which, of course, defeats the purpose of the change.

Temperature of formation, except where actual determination

[1] Buddington, A. F.: High-Temperature Mineral Associations at Moderate to Shallow Depth. ECON. GEOL., vol. 30, pp. 205–222, 1935.

is possible, is best judged by mineralogy. If mineralogy is adhered to and texture ignored, less difficulty is encountered than if the two features are combined. Buddington has pointed out the logic of considering a deposit composed of fine-grained quartz, orthoclase, and molybdenite (such as the Climax deposit) as probably formed at the same temperature as a deposit composed of coarse quartz, orthoclase and molybdenite, as the pegmatitic deposits; also the same for fine-grained and coarse-grained tin and tungsten deposits.

This seems to fit with general experience, from candy making to rock formation, that texture does not depend primarily on temperature but on rapidity of super-saturation and consequent precipitation. We do not think of rhyolite as formed at low temperature and pegmatite at high, but that in rhyolite crystallization was rapid and crystals small, whereas in pegmatite the change was slow and conditions were favorable to the growth of large crystals.

That high temperature does not particularly favor coarse crystallization is at least suggested by vugs lined with coarse minerals that are common in veins of fine texture. The vug minerals likely formed from solution that was reaching supersaturation less rapidly than when the earlier veins were formed and therefore could form larger crystals. The temperature may have remained the same, or may have been lower or even higher.

Depth Classification.—It seems best to keep depth classification independent of temperature classification or to combine them in a compound term. Buddington points out that if Lindgren's temperature classification and depth classification are combined, there are nine possibilities but that all are not likely to be susceptible of clear determination. Texture has been quite generally thought an indication of depth of formation, especially in a mineral such as quartz, and this is probably to a considerable degree true. Under deep-seated conditions rapid supersaturation is not likely to result from rapid loss of temperature, rapid escape of gases or any rapid change. The slow change is favorable for growth of large crystals, and course texture is doubtless characteristic of deep deposits.

Solutions at shallow depth may lose both heat and included gases rapidly and therefore reach supersaturation rapidly and upon crystallization yield fine textures whether at high, intermediate or low temperatures. Supersaturation need not be rapid at the surface, however, especially if the temperature of the solution be low, and one might expect that in near-surface deposits those formed slowly at low temperature might be of coarser texture than those formed rapidly at high temperature.

It would seem, therefore, to make for definiteness and clarity if the terms for temperature of formation and for depth of formation were independent. They could, of course, be combined as hypothermal-shallow or epithermal-shallow.

Buddington points out that several metals occur as both deep and shallow deposits formed at the same temperature, but differing decidedly in texture. Among these are the deep and shallow tin, tungsten, and molybdenum deposits.

He does not include gold in this group. If the coarse and fine-textured molybdenum deposits, such as the pegmatite type and the fine-grained quartz-orthoclase type of Climax, are regarded as of the same temperature of formation, would it not be logical to regard the coarse quartz-gold veins of the Mother Lode and the fine-textured quartz-adularia-gold veins of the Tertiary volcanics as of the same temperature but formed at different depths. Spurr,[2] who, in his idea of telescoped deposits, postulates a similar temperature of deposition for deposits of different texture in tin, tungsten, copper, zinc, and lead, regards gold as deposited at both high and low temperatures.

Many difficulties are avoided if we think of gold also as having a characteristic temperature of deposition that may be reached far below the surface or near the surface.

There are, to be sure, mineralogical associations in some deposits that seem opposed to such a conclusion, but if the possibility be considered that gold follows many of the other metals in having a rather definite temperature of deposition and not a recurrence of deposition at widely different temperatures, it may well

[2] Spurr, J. E.: The Ore Magmas, p. 301. McGraw-Hill Book Co., 1923.

result that the seeming mineralogical inconsistencies will disappear.

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WATERS, MAGMATIC AND METEORIC.

Sir.—I have read with great interest Waldemar Lindgren's paper[1] dealing with the neglected subject of magmatic and meteoric waters.

It is very refreshing to note the author's decision to leave the controversy regarding the origin of the gold deposits of the Witwatersrand to those who have had sufficient experience of the occurrences to be able to speak with authority, and my only excuse for taking up your space is to provide information which will probably prove of interest regarding certain waters encountered at depth on the Rand.

First, it must be said that the statement on page 474 that "From the mines in the upper part of the Witwatersrand system the town and the mills draw all the water needed. Thus, that part of the beds would appear to be permeable," is quite incorrect. I believe that I am right in saying that water is only encountered in the beds of the Main-Bird Series (from which the major portion of the gold won is produced) where faults or dikes are encountered. The unfractured quartzite, shale and conglomerate beds are quite dry, and, far from sufficient water being produced from the underground workings for the use of Johannesburg and the mines, a vast undertaking known as the Rand Water Board is in existence. From the earliest days of Johannesburg water for domestic purposes was scarce, and it was not until 1899 that boreholes in the dolomite formation south of the town produced even a bare sufficiency. At the outbreak of the Anglo-Boer War, twenty-three mining companies, milling approximately 12,000 tons of ore per day, had participated in a syndicate which had spent £340,000 in the acquisition of water sources, sinking bore-

[1] ECON. GEOL., vol. XXX, pp. 463–477, 1935.

holes, etc. It was later calculated by the Chamber of Mines that by 1908 the requirements of the mines alone in "new" water (*i.e.* apart from conserved and naturally occurring water in the mines) would be at the rate of 20 million gallons per day. During the year ending March 31, 1935, the mines of Johannesburg took 3,336,111,000 gallons of water from the Rand Water Board, three-quarters of which amount was obtained from the Vaal River, about 30 miles distant. A further 4,713,310,500 gallons was consumed by the municipalities and railways on the Witwatersrand.

Few analyses of naturally occurring water in the Rand mines have been published, but water encountered in a fissure of the sixth level on the Geduld Mines contained 440.2 parts per million of sodium chloride, 93.2 parts of sodium sulphate, and smaller amounts of carbonates.[2] The flow of water encountered in quantities in the East Rand Proprietary Mine upon intersections of fissure zones with which considerable dislocations of the strata are associated has at times been as great as 4,500,000 gallons per day with a pressure of 1,000 lb. per sq. inch.[3] Sulphuretted hydrogen is invariably associated with this water, which is otherwise of considerable purity, only 160 parts per million of dissolved solids being present when the water was first encountered, the hardness on the Clark scale being nil. A later analysis showed that the dissolved solid content had risen to 400 parts per million, with a hardness of 7 degrees. For comparison, it may be stated that water from the adjacent dolomites had a hardness of 21 degrees with 200 parts per million of dissolved solids.

The fissure zones are commonly hundreds of feet in thickness and are invariably associated with extensive faulting of the adjacent strata, but the fact that they are comparatively soon drained to the level of the lowest holings shows that the water is not stored in the pores of a permeable rock but is confined entirely to the fissures, the great pressure encountered being doubtless due to the amount of free movement possible in the fissure reser-

[2] Cowles, E. P.: Jour. Chem. Met. and Min. Soc. of So. Africa, March, 1932, p. 211.

[3] Bok, L.: Proc. Empire Min. and Met. Cong., 1930, Pt. II, pp. 274–5.

voirs. Bok considers the water to be of meteoric origin. In 1932 the fissure zone had been intersected at a depth of over 6,000 feet below the surface and drained to the 5,700 foot horizon.

On the City Deep Mine no great flows of water have been encountered, but it is noteworthy that at a depth of 6,750 feet a small feeder of water containing sulphuretted hydrogen was encountered when mining operations cut a small fissure in the footwall quartzite near its contact with underlying shale, at a distance of several hundred feet in the footwall from the Main Reef (conglomerate). Small quantities of water are often encountered where faults or dike contacts are intersected, sulphuretted hydrogen being nearly always present. In places, methane in small amount is associated with such occurrences. In unaltered, unfissured quartzite or conglomerate, water is hardly ever found —never in my experience—and it is a moot point whether even the water in fissures or dike contacts is not water sent down the mine for drilling and watering down the rock surfaces which, in its return to the sumps along drains, has encountered one of these ramifying openings and made its way into a fissure which is later cut by mining operations at greater depth.

In conclusion, whatever may have been the state of affairs at the period in geological history during which Professor Graton considers the gold of the Witwatersrand to have been deposited from hydrothermal solutions, there is not, at the present time, any sign that the conglomerates or quartzites of the Witwatersrand System are in the least degree permeable.

The mere fact that ninety per cent. of the trained workers on the Rand who, in most cases, have spent years of work on the deposits, are in disagreement with Graton's hypothesis concerning the origin of the gold, should cause one to be chary of drawing too close a parallel between those deposits and the Lake Superior Copper occurrences; even the origin of the latter is yet to be definitely proved, as Lindgren, with his usual flair for putting his finger on the point at issue, points out.

Professor Lindgren appears to me to be rendering a great service to the science of economic geology when he calls for mod-

eration in the growing belief, especially in America, that ore deposits are, almost perforce, all of magmatic origin, using that phrase in a wide sense. It is very probable that most deposits are of such origin, but to apply the belief to particular deposits against the weight of evidence can only result in a halt in the march of geological knowledge and in the faith which mining operators are beginning to feel in the science.

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REVIEWS

The Gold Hill Mining District, Utah. By T. B. NOLAN. Pp. viii + 172, figs. 31, pls. 15. United States Geological Survey, Prof. Paper 177. Washington, 1935. Price, $1.25.

Few quadrangles present such a wide range of geological phenomena in such complicated and yet clearly co-ordinated and causally related sequence. Consequently the report is one that holds the reader's interest throughout. The geologic history of the quadrangle includes a long and thick stratigraphic sequence, deep-seated and volcanic igneous activity, both endomorphic and exomorphic igneous metamorphism, a complex sequence of structural cycles, mineralization and ore deposition ranging in physical conditions from magmatic to the latest and coolest hydrothermal, with instructive examples of structural control, the influence of chemical and physical character of ores and walls on supergene alteration, and physiographic processes. All of these subjects are handled in a thorough and scholarly way. The report is a great credit to the author and to the organization that permitted him to devote the time necessary for such thorough handling of such diverse geologic problems.

Accompanying the report is a geologic map of the Gold Hill quadrangle on the scale of 1 : 62,500, a structural map on the same scale, and a more detailed geologic map of the mineralized portion on the scale of 1 : 24,000. The topographic sheet of the quadrangle is very useful in reading the report and should have been included for the convenience of the reader.

The Gold Hill district lies along the west central boundary of Utah and comprises the Clifton Hills that constitute the north end of the Deep Creek Mountains. This report is the first complete account of the geology of the area.

The sedimentary record begins in the Lower Cambrian and extends to the Lower Triassic, without long-continued time breaks. From Middle Cambrian on, the sediments are largely limestone and dolomite. Most of the dolomites are explained as the products of reworking of calcareous muds by the sea in shallow water during periods of little or no deposition. Three facies of Carboniferous rocks are recognized, but are very unequally represented and in part not clearly differentiated. They are brought into more or less close contact by two large thrust faults. An eastern facies is represented only by the Mississippian Woodman forma-

tion, which is lithologically like the Woodman of the western facies. The central facies includes three formations, the Ochre Mountain limestone, the Manning Canyon formation, and the Oquirrh formation, younger than the Woodman and ranging in age from upper Mississippian to early Permian. Lithologically, the Ochre Mountain limestone is alike in both the central and western facies. The Manning Canyon formation is a little more quartzitic and less calcareous in the central facies than in the western facies. The Oquirrh formation shows a much greater lithologic difference in the two facies, the western facies including 3,000 feet of limestone whereas the central facies is prevailingly sandy and shaly throughout. There is a resumption of the sedimentary record in the Eocene, and again by gravel and clay in the Pliocene and Recent. The sediments have an aggregate thickness of the order of magnitude of 30,000 feet.

The igneous rocks include an extensive late Eocene or Oligocene intrusion of quartz monzonite and related porphyry dikes and aplites and late Pliocene lavas and pyroclastics. The former occupy the east-central part of the quadrangle and are genetically related to the mineralization. The latter are confined to the northwestern part of the quadrangle outside of the mineralized area. The quartz monzonite is limited on the north and south by large transverse faults and on the west by the Ochre Mountain thrust. The latter is believed to have caused the fracturing that permitted the emplacement of the monzonite. The monzonite varies in composition from granite to quartz diorite. The porphyry dikes range from granite porphyries to basalts, and occur both in the monzonite and in the sediments to the north on Dutch Mountain. The aplites are confined to the monzonite. They occur as cylindrical masses and as dikes.

The structural history of the district is both complex and unique. Five cycles ranging from late Cretaceous or early Eocene to post-monzonite have been deciphered. In addition extensive late Pliocene normal faulting has occurred. The cycles are divisible into an early compressional stage and a later relaxational stage. In the early compressional stage, folding is dominant in cycles 1 and 2, low angle thrusting in cycle 3, and transverse faulting with horizontal movement in cycles 4 and 5. This change is interpreted as reflecting yielding under progressively lighter loads. The later relaxational stage is expressed in normal faulting. The normal faults decrease in number and intensity with succeeding cycles. The explanation is offered that the additional strength or rigidity imparted by successive cycles made relaxational movements less and less necessary. The late Pliocene normal faulting has throws up to 2,500 feet and has been an important factor in determining the present topography.

The description and discussion of igneous metamorphism is unusually interesting and presents some unconventional ideas. Four successive stages are represented in the sedimentary rocks; (1) recrystallization;

(2) alteration to silicate minerals; (3) alteration to jasperoids; (4) dolomitization. Recrystallization is explained as the work of circulating waters set in motion by the magma rather than that of heat. This conclusion is based on the fact that limestones above the Ochre Mountain thrust are unaffected whereas limestones immediately beneath them under the thrust are highly altered, and that some limestone roof pendants are unaffected. It is noteworthy that recrystallization in limestones was not accompanied by reaction between carbonate and silica, whereas in shale andalusite hornfels was formed. Alteration to silicates was guided by pre-existent minor fractures. Avoidance of the term "contact" metamorphism is explained on the ground that this alteration shows little relation to the actual monozonite contact. It is not obvious why the useful term pyrometasomatism is likewise avoided. Two types of silicate rocks occur, one consisting of green diopside and brown garnet and the other of white bladed wollastonite. Alteration to jasperoid is widespread and occurred in general near the monzonite contact. Dolomitization is also widespread, but at some distance from the contact, and is dependent on fracturing.

The quartz monzonite has undergone a closely parallel series of alterations but on a much less extensive scale. Corresponding to the silicates in the sediments is the formation of garnet, diopside, and orthoclase in the monzonite. The occurrence of orthoclase in the monzonite and not in the sediments is ascribed to the abundance of alumina in the former and its virtual absence in the limestones. A second stage of alteration is the development of sericite and chlorite. A third stage is silicification, corresponding to the jasperoid formation in the limestones. It occurred mainly on a microscopic scale but apparently continued over a long period, in that the early stages are accompanied by chlorite and sericite and the late stages by barite and ankerite.

Corresponding to the progressive change in igneous metamorphism a progressive change in the character of mineralization also took place. The author found it convenient to classify the deposits, on the basis of form and genesis combined, into three groups: pipes, veins, and replacements. The pipes are pegmatitic masses at the intersections of fissures and produced mainly scheelite. The veins are divided into three groups representing successively lower-temperature deposits: (1) Veins with gangue silicates containing tungsten copper, and gold; (2) Veins of quartz and metallic sulphides with silver and lead values; (3) Veins of carbonates and sulphates (barite) with or without quartz and with very scarce sulphides. The first two groups are further subdivided into types corresponding to successively lower temperature of deposition. The most abundant and productive veins are the quartz veins with base metal sulphides. Though the veins are persistent, ore shoots are small and in-

frequent. The largest ore bodies of the district are arsenic replacement deposits in which the hypogene mineral is arsenopyrite. Less important replacement deposits carry copper, lead, and silver values. Ore deposition spanned the same physical-chemical range as igneous metamorphism and was contemporaneous with it.

A significant section of the report is the discussion of the areal relations of the ore deposits with respect to zoning. Except for the restriction of the high-temperature deposits to a narrow zone of normal faulting related to the supposed intrusion channel of the monzonite, time of ore deposition appears to have been of more significance than the usual space and temperature factors that give rise to zoning in determining the type of deposit formed. Younger low-temperature deposits are areally superimposed on the older high-temperature deposits. Throughout the period of mineralization repeated fracturing took place. Because of these relations it is suggested that when no fracturing occurs during mineralization zoning may develop; but that, when fracturing is recurrent during mineralization, later channels are provided in areas that would otherwise have been sealed shut, and superposition of types occurs instead of zoning. To this recurrent fracturing during ore deposition is ascribed also the small size of the ore bodies and the ore shoots. Because of it mineralization was not long continuous enough at any one place to form large ore bodies. Another inference from these areal relations is that ore deposition must have extended over a long period. Just as the igneous metamorphism was bounded above by the Ochre Mountain thrust, so that thrust also limited the upward extent of the mineralization.

Superficial alteration of the ore deposits is almost restricted to oxidation and is strikingly dependent on the physical and chemical character of the ores and wall rocks. The silicate gangue deposits and the barite veins are practically unaltered. The quartz sulphide veins and the copper, lead, silver replacements are completely oxidized and the ores are largely members of the jarosite group. The arsenic replacements present the most spectacular alterations. Their oxidized zones are masses of scorodite. The outcrop of the Gold Hill mine occupied an area 300 feet by 200 feet.

The report portrays an unusually complete picture of the everchanging results effected by emanations given off by a solidifying intrusive. A student of ore deposits will read it with a feeling of pleasurable satisfaction.

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Lehrbuch der Kohlenpetrographie. By E. STACH. Pp. 293, figs. 173. Gebrüder Borntraeger, Berlin, 1935. Price, 18 Rm.

The study of coal by petrographic methods has advanced far enough to warrant the publication of a text-book that will describe those methods that have proven most satisfactory in the investigation of the minute character of coals, more particularly those that have been developed in the "coal-petrographic" laboratory of the Prussian Geological Survey, mainly by the author and his associates. The excellent photomicrographs that illustrate the text confirm the correctness of the author's statement that he has succeeded by the use of oil-immersion lenses in observing details in coal thin-sections that have not been observed heretofore. Many of his illustrations are of sections magnified 1000 diameters, and are remarkably clear.

The book contains a systematic discussion of coals, a description of the methods employed in studying them, and interpretations of the objects seen under the microscope. Vitrite, durite, and fusite, and their varieties are defined and then described in detail. Following this, which constitutes the major portion of the volume, is a brief description of inflammable shales (Brandschiefer), which are defined as coaly materials containing 30–50 per cent. of ash.

In his chapter on petrographic coal analysis the author calls attention to the fact that the analyses of coals, until very recently, have been limited to chemical methods, although it is now well known that the special qualities of the various types of coal depend almost exclusively upon the character of their components rather than upon their chemical composition. He thereupon outlines the methods which, in his experience, are the most satisfactory for preparing coal dust and small grains of coal for qualitative study under the microscope by transmitted and by reflected light, and concludes with a few pages on quantitative methods.

The book closes with a bibliography of 919 entries, mainly upon the petrography of coal and studies on the nature and source of its various components.

While much of the material of the book has appeared in other places, it is only in this volume that it has been collected in a continuous narrative, which should be of considerable value to most students of the nature of coal. Its most striking feature, however, is its series of excellent figures.

W. S. BAYLEY.

A Geography of Europe. By RAOUL BLANCHARD AND R. E. CRIST. Pp. 490, figs. 188. Henry Holt & Co., New York, 1935. Price, $3.50.

The 60 pages of Part I cover the mountains, plains, rivers, coasts, climates, vegetation, and settlement of Europe. The succeeding parts cover different divisions of Europe such as western, northern, central, etc. The various included countries are discussed separately and very briefly, according to their major political or economic divisions; physical features, population, and industries, are given. A concluding part deals with the population, resources, dependencies and forces which unite and divide Europe.

The volume serves as a reliable, compact digest of the geography of Europe. Because of so many political divisions, the discussions of each part are necessarily brief. It serves, however, to bring together in one volume a mass of scattered data for ready reference.

A Comprehensive Treatise on Engineering Geology. By CYRIL S. FOX. Pp. 392, figs. 95. Van Nostrand Co., New York, 1935. Price, $7.50.

This book deals with principles and applications. Part I, Building Materials, is initiated by a brief discussion of the solar system, the Earth, and radio-activity. This is followed by the common rock-forming minerals and the principal rock types—their character, mode of occurrence, and microscopic determination. The last, however, is useless, since its brevity makes for confusion rather than clearness. The 25 photomicrographs of thin sections likewise seem out of place.

Part II, Field Operations, deals briefly with isostasy, folds, faults, and earthquakes, followed by the stability of hillsides, quarrying and tunneling, retaining walls, and building sites. The part relating to earthquakes and their effects is interesting, since the author had opportunity for firsthand observation in India.

Part III, Water Supply, deals briefly with meteorology, topographic effects, valleys, streams, and coastal erosion, followed by surface and underground water supply and the quality of water.

The volume records considerable firsthand information, gained mostly in India and relating to India. The arrangement of the material, however, seems haphazard and out of balance. Simple elementary material is interspersed with abstruse geological topics that have little bearing on the subject and are too briefly presented to be grasped by the student. Imagine teaching an engineer petrography in 13 pages, of which 5 are devoted to a method of making thin sections! Although the geology is too sketchy to be of much value to the student, a number of interesting applications are given, relating particularly to the subjects of Parts II

and III. The book, on the whole, should prove a useful supplement to more comprehensive works on engineering geology.

Einführung in die Grundlagen der Historischen Geologie: Bd. I. Die Ammoniten-, Trilobiten- und Brachiopodenzeit. By R. WEDEKIND. Pp. 109, figs. 19, pls. 27. Ferdinand Enke, Stuttgart, 1935. Price, 6.50 M.

The author feels that the current text-books of historical geology are burdened with an excess of names of fossils that follow consecutively without any discussion of the mutual relationships of the objects named, so that the subject does not appeal, as it should, to the beginner in the study of paleontology or stratigraphy.

He proposes therefore to prepare a new text-book in which the names of fossils are not the important facts, but rather, what their orderly appearance in the rocks and their changes in character in succeeding formations signify with respect to time relations.

In that part of the book now presented he discusses the time periods of the ammonites, trilobites and brachiopods, because he believes that by the study of the remains of these animals the relationship between paleontology and historical geology may be easily illustrated.

After a description of the structure of the hard parts of the forms discussed, they are classified into groups characteristic of successive periods of time, and those groups important for diagnostic purposes are described sufficiently to enable them to be identified. There is very little stress placed on the features of individual species—the emphasis in all cases being placed upon the features of the groups. The illustrations show the characteristics of the groups, the unessential details being omitted.

W. S. BAYLEY.

BOOKS RECEIVED.

L. B. RILEY.

Thirteenth, Fourteenth and Fifteenth Annual Reports of Research Council of Alberta, Canada. (1932–34.) Reports Nos. 28, 29, 32 (one volume). Pp. 87. Univ. of Alberta, Edmonton, 1935. 35 cts. Fuels, general geology, road materials, natural gas; lists of publications.

Report of Committee on Batholiths. F. F. GROUT, Chairman. Nat. Research Council, Div. of Geol. and Geog., Ann. Rept. 1935, Appendix A. Washington, 1935. Three separately bound papers. **Exhibit A:** Review of Progress in the United States for the year 1934. Pp. 15. **Exhibit B:** Annotations of Selected Papers on the Mechanics of Igneous Invasion, with special reference to batho-

liths. Pp. 54. **Exhibit C**: Comments on Magmatic Stoping, by authors of geological books and papers. Pp. 47.

Report of Committee on Measurement of Geologic Time. A. C. LANE, Chairman. Nat. Research Council, Div. of Geol. and Geog. Ann. Rept. 1935, Appendix K, Exhibits A–K. Pp. 85. Washington, 1935. Recently determined dates in geologic history; advances in methods and technique. Bibliography. Age of many igneous rocks, hence of any related ore deposits.

Some Facts about Ore Deposits. G. M. BUTLER. Pp. 98. Univ. of Arizona, Bull. vol. 6, No. 6. Tucson, 1935. 15 cts. Many fallacies of mining geology, popular in most districts, are exposed; the truth is outlined concisely and simply.

The Minerals of Franklin and Sterling Hill, Sussex County, New Jersey. CHARLES PALACHE. Pp. 135, pls. 19, figs. 199. U. S. Geol. Surv. Prof. Paper 180. Washington, 1935. 30 cts. Description of 148 minerals occurring at "Franklin Furnace." The district is the type locality for 32 of these, and the only known locality for 30. The geologic background is briefly outlined; minerals are classified, according to paragenesis, as: primary, skarn and recrystallization, pneumatolytic, hydrothermal vein, and surface oxidation.

Evolution of the Congo Basin. A. C. VEATCH. Pp. 183, pls. 10. Geol. Soc. of America, Mem. 3. Washington, 1935. Geol. maps: Two 1: 10,000,000, two 1: 2,500,000. General geology and geomorphology. Placer diamond fields occur at intersections of post-Miocene valleys with fossil stream beds of Triassic age; a few placers in Triassic stream beds. Source of diamonds was probably from north or northwest.

Outline of the Geology of the Musoma District, Tanganyika. G. M. STOCKLEY. Pp. 64. Geol. Surv. Tanganyika Territory, Bull. 7. Dar es Salaam, 1935. 4s. Three geol. maps. Gold and pyrite in quartz veins, in part residually enriched near surface.

Microscopic and Petrographic Studies of certain American Coals. R. THIESSEN AND G. C. SPRUNK. Pp. 71, figs. 42. U. S. Bur. Mines, Tech. Pub. 564. Washington, 1935. 10 cts. Six coal beds from the Appalachian region are described.

Statistical Appendix to Minerals Yearbook, 1934. O. E. KIESSLING. Pp. 434. U. S. Bur. Mines. Washington, 1935. $1.00. Statistics formerly published as "Mineral Resources of the United States." Present plan of publication is (1) mimeographed summaries of more important information; (2) in June, a bound volume; (3) corrected and supplemented by various data. The last, bound in one volume, is issued under above title.

SOCIETY OF ECONOMIC GEOLOGISTS

The sixteenth annual meeting of the Society was held jointly with the Geological Society of America at the Waldorf-Astoria Hotel in New York on December 26 to 28, 1935.

Otto Stutzer, the retiring president, delivered an address entitled "Carbon Dioxide Eruptions from Coal Seams in Lower Silesia" before a large audience at the close of the joint morning session on December 27. A luncheon was held in his honor immediately after the address. Sixty-seven members and guests attended. Short speeches of welcome to Dr. Stutzer were made by Edward Sampson and J. T. Singewald, Jr.

Seventeen papers were presented at afternoon sessions on December 26 and 27, as follows: Quicksilver Deposits of Terlingua, Texas, by C. P. Ross; Nodular, Orbicular, and Banded Chromite in Northern California, by W. D. Johnston, Jr.; Alkaline and Acid Solutions in Hypogene Zoning at Cerro de Pasco, by L. C. Graton and S. I. Bowditch; Peculiar Hydrothermal Copper-bearing Veins of Northeastern Colorado Plateau, by R. P. Fischer; Ore Deposition South of Ouray, Colorado, by R. S. Moehlman; The New Gold Locality at Guillet Lake, N. W. Quebec, by B. T. Denis; Zonal Relations of the Gold Deposits of Nova Scotia, by W. H. Newhouse; Paragenesis of Pyrrhotite, by G. M. Schwartz; Geologic Work of Tennessee Valley Authority, 1933–1935, by E. C. Eckel; Recent Geologic Studies on Long Island, New York, with Respect to Ground-water Supplies, by D. G. Thompson, F. G. Wells and H. H. Blank; Effect of a Sea-level Canal on Ground-water Level in Florida, by Sidney Paige; Rôle of Physical Chemistry in Stratigraphic Problems, by G. R. Mansfield; Sedimentary Magnesite in the Boulder Dam Region, by W. W. Rubey and Eugene Callaghan; Structure and Significance of Clastic Dikes, Ouray District, Colorado, by W. S. Burbank; Asbestos Deposits of Thetford District, Quebec, by H. C. Cooke; Bedding Replacement Deposits of the Illinois Fluorite Field, by L. W. Currier; Limestone Mines in Pennsylvania, by R. W. Stone.

The sessions were well attended, and lively discussion was aroused by many papers. Thanks of the Society are due to the Geological Society of America for its cordial hospitality and coöperation, and to Walter H. Newhouse for his work as chairman of the Program Committee.

The election of officers was announced as follows: President for 1937, R. H. Sales; Vice-President for 1937, Adolph Knopf. Vice-Presidents

for 1936: for Africa, E. T. Mellor; for Asia, K. Inouye; for Australia, L. K. Ward; for Europe, H. A. Brouwer; for North America, E. S. Moore; for South America, W. F. Walker. Councillors for 1936–1938: G. R. Mansfield, H. B. Kümmel, E. L. Bruce.

The following new members were declared elected:

Ian Campbell, Pasadena, California,
Rollin Farmin, Grass Valley, California,
Donald McCoy Fraser, Bethlehem, Pennsylvania,
Vincent P. Gianella, Reno, Nevada,
Ralph E. Grim, Urbana, Illinois,
Charles F. Park, Jr., Washington, D. C.,
John Calvin Reed, Washington, D. C.,
Waldemar T. Schaller, Washington, D. C.,
Peter Trotzig, Stockholm, Sweden,
Ralph Tuck, Anchorage, Alaska,
Philip D. Wilson, New York, New York.

SCIENTIFIC NOTES AND NEWS

H. Foster Bain was recently the guest of honor at a farewell dinner given by engineers and geologists in Washington, D. C., prior to his departure for Japan.

William B. Heroy, chief geologist, Consolidated Oil Corporation, now has his office in Room 2763, 630 Fifth Avenue, New York.

J. O. Haas, Chief of the Government Petroleum Survey in the French Congo, has been visiting the Rand.

R. B. Young has returned to Johannesburg from London.

A. W. Carlyle has left Northern Rhodesia to join the Union Corporation, Johannesburg.

Reginald A. Daly, Sturgis-Hooper professor, Department of Geology, Harvard University, has been awarded the Penrose Medal of the Geological Society of America.

Lewis G. Weeks, chief geologist, Standard Oil Company of Argentina, lately returned from a visit to England and Scotland and various oil fields in the United States.

Alfred C. Lane, professor of geology and mineralogy at Tufts College, has preferred to resign his position rather than to take the required teachers' oath of allegiance.

The American Institute of Mining and Metallurgical Engineers will hold its Annual Meeting in New York, February 17–21. The annual dinner will be on February 19, at the Commodore. The division of Mining Geology will hold a joint session with the Industrial Minerals division Tuesday afternoon, February 18, and on Thursday, February 20, the following papers will be presented: The Corocoro Copper District of Bolivia, by A. Berton; Formation of the North-South Fractures of the Real del Monte Area, Pachuca Silver District, Mexico, by E. Wisser; Economic Applications of the Insoluble Residue Method, by H. S. McQueen; Succession and Temperature in the Formations of Ore Deposits of Magmatic Affiliations, by W. Lindgren; Ground Preparation and Mineral Deposition, by H. Schmitt; Structure and Mineralization along the London Fault, Colorado, by Q. D. Singewald and B. S. Butler.

The American Association of Petroleum Geologists will hold its twenty-first annual meeting on March 19–21 at Tulsa, Oklahoma, with headquarters at the Mayo Hotel. The following are chairmen of the special committees: Frank R. Clark, Marathon Oil Company, committee on arrangements; W. B. Wilson, Gypsy Oil Company, committee on entertainment; Ira H. Cram, committee on technical program.

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